JN-RC-Report Series JNES-RC-2013-1002

Proposal of Technical Review Guidelines for Structures with Seismic Isolation

平成 25 年 7 月
July 2013

独立行政法人原子力安全基盤機構
Japan Nuclear Energy Safety Organization

独立行政法人　原子力安全基盤機構　総務部　管理グループ
〒105-0001　東京都港区虎ノ門4－1－28
電　　　話：03-4511-1240
ファックス：03-4511-1298
電子メール：kanrig-soumu@jnes.go.jp

Administration Group
Personnel and Accounting Division
JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION（JNES）
4－1－28 Toranomon, Minato-ku, Tokyo, 105-0001, Japan
Ｔｅｌ：+81-3-4511-1240
Ｆａｘ：+81-3-4511-1298

Proposal of Technical Review Guidelines for Structures with Seismic Isolation

Equipment and System Evaluation Group, Seismic Safety Standards and Test Group
Seismic Safety Department

Seismic isolation technology can be broadly classified into building isolation and equipment isolation, both of which have been extensively studied by the nuclear field such as the former Japan Atomic Energy Research Institute, nuclear industry and universities and also by the non-nuclear field for more than a few decades. Consequently, owing to results of research accomplishments and construction experiences, seismic isolation technology has earned recognition as a mature technology. On the basis of such accomplishments, the Regulatory Guide for Reviewing Seismic Design was revised (in September, 2006). In this Guide, requirement for enhancing the condition of design basis ground motion and recognition of the seismic isolation technology were included. Furthermore, existence of the remaining risk was recognized and the mentioning of the rigid structure in the former Review Guide for Seismic Design was eliminated. Thus, the possibility for application of the seismic isolated structures had further increased.

Niigata-Ken Chuetsu Oki Earthquake (in July, 2007) occurred in the vicinity of Kashiwazaki-Kariwa Nuclear Power Station and the ground motion 2.5 times as big as the design seismic response was observed during the earthquake. The door of the emergency response room failed to open, which seriously hindered the post-earthquake activities. Based on the lessons learned from this earthquake, the licensees have been actively promoting to establish the seismically isolated emergency administrative buildings in their sites in order to successfully carry out post-earthquake activities. Some of the examples include the seismic isolated administrative buildings built in Kashiwazaki-Kariwa Nuclear Power Station and Fukushima Daiichi and Dai-ni Nuclear Power Stations.

In the off the Pacific coast of Tohoku Earthquake (in March, 2011), tsunami struck Fukushima Daiichi Nuclear Power Station and caused the loss of reactor cooling function, leading to the release of radioactive materials from the containment vessel beyond the site boundary. Emergency response activities at Fukushima Daiichi and Dai-ni Nuclear Power Stations were directed at the above-mentioned seismic isolated administrative building, which was effectively utilized even under the situation affected by the main quake and after quakes. Based on these experiences, application for construction of seismically isolated facilities important to safety including administrative building is expected.

On the other hand, there has been a growing trend toward constructing new nuclear power plants in the world. The possibility of adopting seismic isolation technology is increasing for the purpose of standardizing the seismic design, not only in high seismicity countries but also in moderate or low seismicity countries.

The Japan Nuclear Energy Safety Organization (JNES) took over the research achievements on the seismic isolation technology made by the above-mentioned former Japan Atomic Energy Research Institute in October, 2003, and has been formulating the design principle of the seismic isolated structures, and assessing the reduction of remaining risk in case where seismic isolation systems are implemented in the components important for seismic safety. JNES has provided the results of these researches to the International Atomic

Energy Agency (IAEA) and the U.S. Nuclear Regulatory Commission and supports the preparation of the IAEA's seismic isolation standards. Having these as a background, JNES established The Seismic Isolation Standard Subcommittee in FY2009 under The Seismic SSCs Standard Committee, consisting of external experts. The subcommittee collected and examined the opinions on the review guidelines for the seismic isolation structures and incorporated them into JNES's draft Technical Review Guidelines for Structures with Seismic Isolation, and then prepared the final edition.

The policy for establishing the Technical Review Guidelines for Structures with Seismic Isolation was to enable the guidelines to be utilized not only in Japan but also in foreign countries. Specifically, the guidelines cover the entire plant life from the design stage to the decommissioning stage, and can be applied to the respective sites with high, moderate and low seismicity. In addition, both newly established reactors and existing reactors are subject to the guidelines. Also, both of the building isolation and equipment isolation including seismic floor isolation are included in the scope of application of the guidelines, and both horizontal and vertical ground motions are considered. Further, the guidelines provide as many examples and explanations as possible.

Contents

IV. Supplement (Examples of Seismic Isolation Trial Design and Preliminary Assessment)

List of Figures

II. Review Guidelines

IV. Supplement (Examples of Seismic Isolation Trial Design and Preliminary Assessment)

- CHAPTER ii. 1.1, 1.2 -

List of Tables

Ⅰ. Introduction

1. Background, Necessity and Purpose of Establishing the Technical Review Guidelines for Structures with Seismic Isolation

Seismic isolation technology can be broadly classified into building isolation and equipment isolation, both of which have been extensively studied by the nuclear field such as the former Japan Atomic Energy Research Institute, nuclear industry and universities and also by the non-nuclear field for more than a few decades. Consequently, owing to results of research accomplishments and construction experiences, seismic isolation technology has earned recognition as a mature technology. On the basis of such accomplishments, the Regulatory Guide for Reviewing Seismic Design was revised (in September, 2006). In this Guide, requirement for enhancing the condition of design basis ground motion and recognition of the seismic isolation technology were included. Furthermore, existence of the remaining risk was recognized and the mentioning of the rigid structure in the former Review Guide for Seismic Design was eliminated. Thus, the possibility for application of the seismic isolated structures had further increased.

Niigata-Ken Chuetsu Oki Earthquake (in July, 2007) occurred in the vicinity of Kashiwazaki-Kariwa Nuclear Power Station and the ground motion 2.5 times as big as the design seismic response was observed during the earthquake. The door of the emergency response room failed to open, which seriously hindered the post-earthquake activities. Based on the lessons learned from this earthquake, the licensees have been actively promoting to establish the seismically isolated emergency administrative buildings in their sites in order to successfully carry out post-earthquake activities. Some of the examples include the seismic isolated administrative buildings built in Kashiwazaki-Kariwa Nuclear Power Station and Fukushima Daiichi and Dai-ni Nuclear Power Stations.

In the off the Pacific coast of Tohoku Earthquake (in March, 2011), tsunami struck Fukushima Daiichi Nuclear Power Station and caused the loss of reactor cooling function, leading to the release of radioactive materials from the containment vessel beyond the site boundary. Emergency response activities at Fukushima Daiichi and Dai-ni Nuclear Power Stations were directed at the above-mentioned seismic isolated administrative building, which was effectively utilized even under the situation affected by the main quake and after quakes. Based on these experiences, application for construction of seismically isolated facilities important to safety including administrative building is expected.

On the other hand, there has been a growing trend toward constructing new nuclear power plants in the world. The possibility of adopting seismic isolation technology is increasing for the purpose of standardizing the seismic design, not only in high seismicity countries but also in moderate or low seismicity countries.

The Japan Nuclear Energy Safety Organization (JNES) took over the research achievements on the seismic isolation technology made by the above-mentioned former Japan Atomic Energy Research Institute in October, 2003, and has been formulating the design principle of the seismic isolated structures, and assessing the reduction of remaining risk in case where seismic isolation systems are implemented in the components important for seismic safety. JNES has provided the results of these researches to the International Atomic Energy Agency (IAEA) and the U.S. Nuclear Regulatory Commission and supports the preparation of the IAEA's seismic isolation standards. Having these as a background, JNES established The Seismic Isolation Standard Subcommittee in FY2009 under The Seismic SSCs Standard Committee, consisting of external experts. The subcommittee collected and examined the opinions on the review guidelines for the seismic isolation structures and incorporated them into JNES's draft Technical Review Guidelines for Structures with Seismic Isolation, and then prepared the final edition.

2. Policy for Establishing the Technical Review Guidelines for Structures with Seismic Isolation

The policy for establishing the Technical Review Guidelines for Structures with Seismic Isolation was to enable the guidelines to be utilized not only in Japan but also in foreign countries. Specifically, the guidelines cover the entire plant life from the design stage to the decommissioning stage, and can be applied to the respective sites with high, moderate and low seismicity. In addition, both newly established reactors and existing reactors are subject to the guidelines. Also, both of the building isolation and equipment isolation including seismic floor isolation are included in the scope of application of the guidelines, and both horizontal and vertical ground motions are considered. Further, the guidelines provide as many examples and explanations as possible.

Ⅱ. Technical Review Guidelines for Structures with Seismic Isolation

1. Introduction

1.1 History and Activities related to Seismic Isolation Technology in Japan and Other Countries

(1) Results of previous researches in Japan and other countries

1) Japan

The seismic isolation technology is divided largely into two categories: building isolation and equipment isolation. In both nuclear and non-nuclear industries, it is recognized as a matured technology supported by the results of useful researches and implementation examples in past more than two decades.

Japan Atomic Energy Research Institute (JAERI) conducted researches on equipment isolation in the period between 1987 and 2000 (see 1 in the table of references for Part II). As a result of these research activities, JAERI developed a methodology for the quantitative evaluation of how the base-isolated components important to safety might contribute to the lowering of the core damage frequency (CDF). Using of this methodology, JAERI demonstrated that the seismic isolation would significantly contribute to reduce CDF by comparing the case where the equipment isolation was applied to the important components which were identified by seismic PRA and the case where equipment isolation was not applied. JAERI also developed a methodology to evaluate economic effect of the seismic isolation and showed merit of implementing the seismic isolation structure. Furthermore, JAERI designed and fabricated a three-dimensional seismic isolation system based on the concept which was developed by JAERI. JAERI tested the 3D seismic isolation system on a shaking table to evaluate its seismic isolation capabilities in horizontal and vertical directions and effect of the rocking motion. In addition, JAERI accumulate useful data on 3D seismic isolation device by conducting ultimate strength testing of the device. In the testing of the 3D seismic isolation system with actual ground motion, JAERI verified capabilities of the system against the observed ground motion of 86Gal in the horizontal direction and 29Gal in the vertical direction. In order to confirm the validity of the equipment isolation technology, JAERI studied, from the viewpoints of technology and economy, the retrofit equipment isolation technology implemented for Hayward Switchyard in the suburb of Wellington, New Zealand, and demonstrated the availability of the technology. The achievements of those activities were transferred in 2001 to the Nuclear Power Engineering Corporation (NUPEC), which later was reorganized into the Japan Nuclear Energy Safety Organization (JNES). JNES has been continuing unique studies on seismic isolation. In terms of the equipment isolation, NUPEC studied the seismic isolation of floors as well, and The Institute of Industrial Science, the University of Tokyo, conducted the researches on seismic isolation technology for components. The Central Research Institute of Electric Power Industry (CRIEPI) has been continuing researches on seismic isolation of FBR buildings. The Japan Electric Association published guidelines for design of building isolation.

Besides the nuclear industry, the Architectural Institute of Japan published guidelines for design of the seismic isolation in 2000. Since the Hyogo-ken Nanbu Earthquake in January 1995 demonstrated the effectiveness of the seismic isolation that had been applied to the Ministry of Posts and Telecommunications West Building, the seismic isolation technology began to attract greater attention, which led the Japan Society of Civil Engineers (JSCE) and the Japan Society of Seismic Isolation (JSSI) to publish seismic isolation guidelines in 2000 and 2006, respectively.

2) Activities of previous researches in overseas

As to the development of seismic isolation technology for nuclear industries in overseas, the first seismic isolated building in the world was completed in 1985 at the Cruas Nuclear Power Station in France. A seismic isolated building was completed also at the Koeberg Nuclear Power Station in the Republic of South Africa.

The Northridge Earthquake of 1994 in the United States demonstrated the effectiveness of seismic isolation that had been implemented to the USC (University of Southern California) hospital building. The International Organization for Standardization (ISO) established the standard on laminated rubber bearings used for the seismic isolation.

(2) Recent activities in Japan and other countries

1) Japan

The Niigata-ken Chuetsu-oki Earthquake (2007) had its epicenter close to the Kashiwazaki-Kariwa Nuclear Power Station, where earthquake ground motion 2.5 times greater than the design basis level was observed. All seven reactors at the site automatically stopped in response to the earthquake. Each unit maintained the functions for *shutdown*, *cooling* and *containment* without causing safety concerns. Facilities of low seismic classification rating, however, were affected by about 3,700 cases of troubles, including the inability to open the door of the emergency response room, which prevented the smooth execution of emergency response activities. Based on lessons Learned from such experiences, utilities have been pursuing secure post-earthquake activities by introducing the base-isolated emergency buildings. Such a base-solated building was constructed at the Kashiwazaki-Kariwa, Fukushima Dai-ichi and Fukushima Dai-ni Nuclear Power Plant, for example.

Off the Pacific Coast of Tohoku Earthquake occurred at March 11, 2011. Tsunami due to the earthquake seriously damaged Fukushima Dai-ichi NPP and caused the loss of cooling function of the core and release of radioactive materials from the containment vessels to the external environment. At both Fukushima Dai-ichi and Dai-ni NPP, the base-isolated emergency building mentioned above contributed to effective post-earthquake activities in the threat of frequent aftershocks.

2) Collaboration with foreign organizations

The International Atomic Energy Agency (IAEA) proposed 10 working areas in the Extra

Budgetary Program (EBP) donor meeting in January 2009. The seismic isolation technology was included in one of the working areas (WA2). JNES reported its latest findings in the area of seismic isolation technology and provided IAEA and its member states with CD-ROM of the Guidelines. A meeting of WA2 experts was held in December 2012 by the hosting of the U.S. NRC. At this time, JNES distributed updated Guidelines.

In December 2010, the IAEA's International Seismic Safety Center (ISSC) and JNES jointly organized the First Kashiwazaki International Symposium on Seismic Safety of Nuclear Installations, including a workshop on seismic isolation held by JNES and EDF. Active discussions among Japanese and international experts were followed by the adoption of a resolution that emphasized followings:

(i) A need to prepare international standards on seismic isolation through international cooperation

(ii) A need to share knowledge and information on seismic isolation with support from IAEA

(iii) Further improvement of seismic isolation technology through international cooperation with attention to the following:

- Response of base-isolated structure to long-period ground motion
- Effects of interactions between solid and structure
- Effects of vertical motions produced by the coupling of vertical and horizontal ground motions
- Effects of difference in response between isolated and non-isolated structures (in the case of main steam piping, etc.)
- Dealing with the aging of seismic isolation device
- Standardization of test and quality control procedures
- Evaluation of safety margin against ground motion beyond design basis
- Seismic PSA for NPPs with base-isolated facilities
- Impacts of non-seismic external events on base-isolated facilities at NPPs

JNES introduced its approach to the seismic isolation technology at a Regulatory Information Conference (RIC) in response to invitation from U.S. NRC in 2009 and 2011. JNES also introduced and provide the Guidelines to all concerned.

(3) Usefulness of seismic isolation technology

Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities (Nuclear Safety Commission) was revised in September 2006. This revision involved the correction of the design basis ground motion and recognition of the seismic isolation technology. Further, in view of new findings from the Niigata-ken Chuetsu-oki Earthquake (2007) and the Off the Pacific Coast of Tohoku Earthquake (Tohoku Earthquake) in 2011, the design basis ground motion should be greater than the one used for current seismic design.

Given such background, the use of seismic isolation technology at NPPs is expected to be the effective way to increase seismic safety margins of both new and existing facilities and to achieve the further improvement/assurance of seismic resistance and reliability. Therefore, the application of seismic isolation technology to NPPs is expected to accelerate in the future; preliminary studies have already begun toward the use of seismic isolation technology at next-generation reactors.

Lessons learned from the Tohoku Earthquake (2011) have accelerated the implementation of seismic isolation in emergency administration buildings. The idea, which is becoming increasingly common in these days, is to seek comprehensive improvement of seismic safety by combining the seismic safety of nuclear power facilities and the use of seismic isolation for such support facilities. The Tohoku Earthquake (2011) has also reminded us that there were facilities classified in low seismic category could greatly contribute to safety and reliability of the entire plant when their seismic resistance could be improved. Since some of such facilities, like switchyards, are difficult to be seismically improved, the need to implement the seismic isolation for such facilities is expected to be more strongly recognized in the future.

On the other hand, there can be cases of seismic isolation technology being implemented for the standardization of seismic design of SSCs at moderate and low seismicity sites. The need to employ the seismic isolation structure because of this reason is also expected to grow in the future.

The above-mentioned revision of the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities described recognition of residual risk (core damage, failure of containment vessel and public exposure). The Regulatory Guide also withdrew a provision in the previous version of the regulatory guide that said, “Buildings and structures, as a general rule, must be rigid structure.” This facilitated the implementation of a seismic isolation structure into NPPs.

Because of the background described above, the implementation of the seismic isolation structure into NPPs in Japan is expected to begin in the near future. To be ready for the examination of the seismic isolation structure, JNES had held The Seismic Isolation Standard Subcommittee from March 4th in 2010 to January 19th in 2012, and prepared the Guidelines by bringing together the outputs from researches on the seismic isolation technology in past a few decades.

There is also an increasing trend for building nuclear power plants in overseas the seismic isolation technology is likely to be implemented not only in countries where large ground motion is anticipated but also in countries with moderate or low level ground motion, aiming at standardizing the seismic design.

Moreover, IAEA started up a new EBP dedicated to the purpose of producing guidelines for the seismic isolation structures incorporating guidelines of JNES, U.S. NRC and other member states.

JNES, therefore, believes that it can make significant international contributions by providing the Guidelines.

1.2 Basic Concept of Securing Seismic Safety by Implementation of the Seismic Isolation Technology

The common understanding on basic concepts of securing seismic safety by implementation of the seismic Isolation technology is essential to establish the Guidelines. The following describes the basic concepts:

(1-1) The safety of the nuclear facilities is based on the principle of defense in depth reflecting severe accident management related to Fukushima Dai-ich NPP accident (high reliability of components important to safety, installation of safety systems, installation of the containment vessel, severe accident management and mitigation of nuclear disaster), as a basic rule. The concept of seismic safety is basically the same: seismic safety is ensured by the contribution of components important to seismic safety.

(1-2) In the conventional seismic design (strength design) for components, standardization over a long period of time and a high level of quality control have realized excellent reliability of components.

(2-1) However, the revision of the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities and the observation of ground motions which are higher than design basis at the Niigata-ken Chuetsu-oki Earthquake (2007) and Off the Pacific Coast of Tohoku Earthquake (2011) lead to the improving the design basis ground motion Ss. The increasing Ss causes seismic stresses on components to come closer to the allowable stress limit categorized as III As and IV As and the seismic safety margin would decrease. The collection of the seismic capacity data of components important to safety has been progressed. But it is not enough to improve the accuracy of evaluation of the seismic safety margin in a short period.

(2-2) The seismic isolation technology, in each of its two major categories, namely, the building isolation and the equipment isolation, has become matured thanks to the accumulation of results from research activities conducted by industry, academia and government for more than two decades in Japan.

(2-3) The introduction of seismic isolation technology is an effective strategy for the further enhancement of seismic safety.

(2-4) Seismic isolation is classified into two functions. Firstly, it secures seismic safety by reducing acceleration response to ground motion while trying to limit excessive increase of response displacement. Secondly, it maintains the seismic response of the facilities at a similar level regardless of soil conditions, thus trying to standardize seismic design of facilities.

(3-1) “Residual Risks” was recognized because the possibility of stronger earthquake ground motions which may exceed the one formulated as the design basis ground motion Ss exists.

(3-2) The probabilistic risk assessment (PRA) is only provided as a method to evaluate the residual risks. Atomic Energy Society of Japan (AESJ) acknowledged the PRA as mature method and established the standards for procedure of level 1 PRA (evaluation of CDF (core damage frequency)), level 2 PRA (evaluation of the containment vessel) and level 3 PRA (evaluation of the public exposure) against earthquakes and tsunamis.

(3-3) The assessment result of the seismic PRA demonstrated that the seismic isolation would significantly reduce CDF by comparing the case where the equipment isolation was applied to the components which greatly influence CDF and the case where equipment isolation was not applied.

(4-1) The building isolation brings the benefit of reduced response acceleration to all components inside the building, while the equipment isolation benefits components on the isolated base. Both technologies serve the purpose of securing the seismic safety of components important to safety.

(4-2) The implementation of the seismic isolation structure greatly contributes to reduce response acceleration. On the other hand, since the response displacement increases, interface between base-isolated structure/component and non-isolated structure/component (isolated/non-isolated interface) would be typical vulnerability of the seismic isolation structure.

(5) The ensuring the standardization and high reliability [see (1-2) above], and the technical measures of how to cope with the problems unique to the seismic isolation structure such as isolated/non-isolated interface [see (4-2) above] is key issues for design of the seismic isolation.

(6-1) To make the Guidelines effective, provisions on performance and specifications are essential. The provisions related to specifications owe much to research activities conducted over two decades in Japan, which include experiments utilizing shaking tables.

(6-2) In consideration of the two functions of seismic isolation described in (2-4) above, stakeholders in overseas may use the Guidelines at sites in regions of various seismicity (classified as high, moderate and low). It is evidently important to discuss how the seismic isolation structure should be employed in not only high seismicity areas, but also in medium seismicity areas. When employed at low seismicity sites, seismic responses are controlled at a similar level regardless of soil condition, and the seismic design of facilities can be standardized.

(6-3) The Guidelines should be carefully designed to address the entire plant life cycle, giving attention to seismic design, risk assessment, construction, operation and maintenance.

(6-4) The Guidelines specify the main matters subject to the examination of seismic isolation structure implemented at nuclear power facilities.

1.3 Form of the Guidelines

The Technical Review Guidelines for Structures with Seismic Isolation prescribe performance and specific requirements. The Guidelines composed of two parts. Part I includes of the following components: main text, commentary, points requiring attention on review, supplementary information and attachment. Part II provides examples of seismic isolation trial design and assessment, which are meant to help the reviewers deepen their understanding of the contents of Part I.

<Part I>

Part I is introduction in which background, necessity and basic policy of establishing the Technical Review Guidelines for Structures with Seismic Isolation

<Part II>

- Main text:
  The main text describes the matters to be examined for applying seismic isolation structure. Descriptions in the main text specify the matters subject to the examination.
- Commentary:
  Commentaries include technical explanations and design review examples, which are meant to help the reviewers understand descriptions in the main text, and the description about the background of provisions, underlying ideas and so on. The descriptions provided as commentaries are not matters subjects to the examination.
- Points requiring attention on review:
  These describe the points to be remembered or the issues requiring attention by the reviewers and the items to be questioned to utilities. These points are meant to serve as memorandums for the reviewers and are not matters subjects to the examination.
- Attachment:

Documents are attached to help the reviewers understand the contents of commentaries, etc. These attached documents are not matters subjects to the examination.

<Part III>

The conclusion is described in part III.

<Part IV>

Part IV provides examples of seismic isolation trial design and assessment, and descriptions in this part are out of the examination scope. They are not required as so called type approval.

- Trial design examples
- Trial assessment examples

2. Scope

The Guidelines set forth herein shall be used for the evaluation of seismic isolated power reactor facilities.

However, the Guidelines may also be used, as a source of useful information, for the evaluation of other types of nuclear installations that employ a seismic isolation design.

Note that nonconformity to the Guidelines shall not be a cause of rejection if it is justifiable by a good reason.

(Commentary)

- The Guidelines set forth herein are used by JNES when it examines seismic isolation structures implemented at power reactor facilities in response to applications for approval submitted by utilities.
- The Guidelines shall be used for the review of newly built power reactor facilities and already existing ones.
- Useful lessons learned were obtained from Off the Pacific Coast of Tohoku Earthquake in 2011. Seismic isolated facility for emergency activities is planned considering those lessons learned. The concept set forth herein along with the Guidelines will be found useful in connection with such facility as well.
- When a certain part of an application for approval submitted by a utility on account of the implementation of seismic isolation structure at nuclear power generation facilities does not conform to the Guidelines, note that the application shall not be rejected if the nonconformity is brought by technological improvement, advancement or the like, and the achievement of seismic safety of a level equal to or better than the level that would be guaranteed by conformity to the Guidelines is deemed possible.

3. Definitions of Technical Terms

The following defines some of the technical terms used in this document.

Seismic isolation structure	This refers generically to structure that aims to reduce seismic response by the use of seismic isolation devices.
Seismic isolation device	A component consisting of seismic isolation elements to provide seismic isolation function.
Seismic isolation element	Element of seismic isolation device, such as laminated rubber, spring and damper.
Seismic isolation function	Function to support the structure and to reduce the seismic load applied to it.
Base-isolated structure	Whole structure including the superstructure, substructure and seismic isolation devices.
Superstructure	A structure introducing seismic isolation, part above the seismic isolation story, which does not include the seismic isolation devices.
Substructure	A structure introducing seismic isolation, part below the seismic isolation story, which does not include the seismic isolation devices. Structures such as pedestal are parts of the substructure.
Seismic isolation story	An area between the superstructure and the substructure, as a level at which seismic isolation devices are installed.
Non-isolated structure	Structure (building, facility, etc.) that does not employ any seismic isolation structure.
Crossover piping, etc.	Piping, cables and similar components that are installed between base-isolated building/equipment and non-isolated building/equipment.
Equipment isolation	This refers generically to both equipment (component) isolation and floor isolation.
Rigid structure	Structure having a natural frequency that is sufficiently higher than dominant frequencies in the input ground motion.

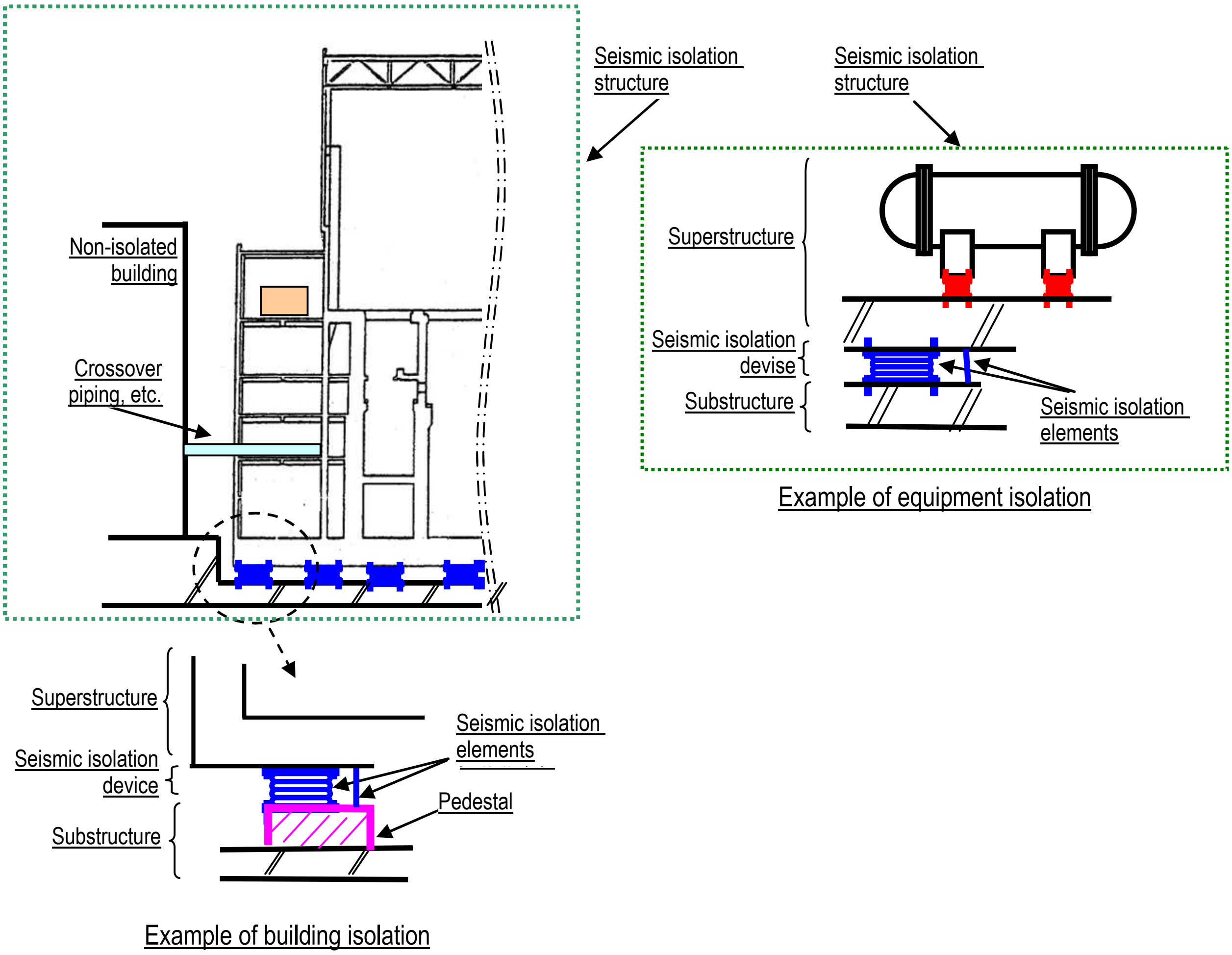


Fig. 3-1 Definitions of Technical Terms

4. Basic Policy

4.1 Preconditions

(1) Scope

- The stages addressed by the Guidelines shall be seismic design, risk assessment, construction and operation.
- The Guidelines may be applied in regions of high, moderate and low seismicity.

(2) Target Facilities

- At newly constructed reactor facilities, the Guidelines shall address buildings and equipment for the reactors of ongoing or next-generation type.
- At existing reactor facilities, the Guidelines shall address equipment.
- Existing reactor facilities for which retrofitting is possible shall not be reject.

(3) Target Types of Seismic Isolation Structure and the Directions of Seismic Isolation

- The type of seismic isolation structure is building isolation or equipment isolation. Any seismic isolation structure that combines building isolation and equipment isolation is allowable.
- The available directions of seismic isolation are the following: only in the horizontal direction, or only in the vertical direction, or in both the horizontal and vertical directions.

(4) Relationship between the Seismic Isolation Function and Seismicity

- Seismic isolation may serve the two following major functions:
  (i) Enhancing seismic safety by reducing acceleration response to ground motion, while trying not to cause excessive increase of displacement response.
  (ii) Maintaining the responses of equipment in the base-isolated structures at a similar level regardless of different ground condition, and standardizing seismic design of equipment.
- In the implementation of the seismic isolation structure, the intended purpose of the seismic isolation is related generally with the seismicity described in (1) above. When implemented in a region of high seismicity, the main purpose meets (i) in the above paragraph. When implemented in a region of low seismicity, the main purpose meets (ii) in the above paragraph. When implemented in a region of moderate seismicity, it is expected that the seismic isolation would serve both function, (i) and (ii).

(5) Determination of the Allowable Displacement Limit of the Seismic Isolation Device

- The allowable displacement limit of the seismic isolation device may be determined using either one of the following two methods:
  (i) Determination based on ultimate displacement of the seismic isolation device such

as rubber bearing.

(ii) Determination based on satisfaction of the performance goal for core damage frequency obtained from the risk assessment.

(6) Input Ground motion for the base-Isolated Structure

- As a general rule, input ground motion for the response analysis of the base-isolated structure shall be obtained from earthquake transmission analysis utilizing the design basis ground motion.
- The design basis ground motion is required to contain low frequency components. In terms of the earthquake transmission analysis, the filtering effect for those components should be checked.

(7) Method of Seismic Response Analysis of Base-Isolated Structure

- As a general rule, seismic response analysis of base-isolated structures shall be conducted using the time history analysis.

(Commentary)

(1) Scope

1) Scope of application through the plant life

- Technical Review Guidelines for Structures with Seismic Isolation address the entire plant life from design to maintenance after the start of operation.
- The current version of the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities (approved by the Nuclear Safety Commission on September 19, 2006; hereinafter referred to as “the Regulatory Guide for Reviewing Seismic Design”) acknowledges the importance of residual risk assessment. The Guidelines, therefore, also address this theme of residual risk assessment.
- For details of seismic design are contained in Chapter 5, for residual risk assessment, in Chapter 6, for construction in Chapter 7 and for operation and maintenance in Chapter 8.

2) Scope in terms of the seismicity

The Guidelines may be applied in regions of high, moderate and low seismicity.

(2) Target Facilities

- At newly built reactor facilities, the Guidelines shall address buildings and equipment for the reactors of ongoing or next-generation type.
- It is technically not impossible to modify existing reactor facilities to achieve the seismic isolation of both building and equipment. However, it is hardly imaginable that an existing building is modified to enable the seismic isolation of the building itself. Therefore, where the Guidelines define the target facilities, the implementation only of equipment isolation is assumed at existing reactor facilities. However, retrofitted

facilities shall not be rejected if the applying seismic isolation retrofit is technologically acceptable.

(3) Types of Seismic Isolation Structure and the Directions of Seismic Isolation

- Seismic isolation structures are categorized into building isolation and equipment isolation.
- Available directions of the seismic isolation are follows: horizontal direction, vertical direction and combination of horizontal and vertical directions.
- Vertical ground motion can be dealt with in different ways: (i) dealt with by three-dimensional seismic isolation design of the building; (ii) dealt with by vertical seismic isolation for equipment; or (iii) not dealt with. An appropriate way can be selected considering the scale of vertical seismic motion and the quake resistance of equipment.
- When a seismic isolation structure is implemented at nuclear power facilities, one may choose building isolation or equipment isolation, whichever is deemed more appropriate, or may combine building isolation and equipment isolation.
- Seismic isolation devices consists of elements like springs and laminated rubber as restoration devices and elements like oil dumpers and friction dumpers as damping devices. Since a wide variety of such elements have been developed, the Guidelines do not specify the type of the seismic isolation devices to be used. As the technology for the designing and manufacturing seismic isolation device are already established and put to practical use, the choice of seismic isolation device shall be by thought of utilities. Therefore, it would not be appropriate for the Guidelines to specify the type of seismic isolation equipment to be used.
- The development of seismic isolation device should continue in the future. This is another reason for not having the Guidelines specify the type of seismic isolation device to be used.
- Based on the above considerations, and assuming that tasks such as the development of seismic isolation devices and the verification of its reliability, as well as the development of design methodology and the verification of its validity, are properly attended to by utilities and other organizations, the type of seismic isolation equipment to be used or the design methodology to be employed are out of scope of the Guidelines, and the Guidelines give attention mostly to requirements concerning the implementation of a base- isolated structure at nuclear power facilities.

(4) Relationship between the Seismic Isolation Function and Seismicity

- It is commonly acknowledged that seismic isolation serves the purpose of reducing the seismic load. However, the standardization of seismic design is another major purpose of seismic isolation. The implementation of a seismic isolation structure ensures that it maintains the responses of equipment at a similar level even if the subject ground conditions vary, and standardize seismic design across facilities.

- The intended function of seismic isolation is generally related with the seismicity. In general, the reduction of seismic load is the main purpose in a region of high seismicity, and the standardization of seismic design is the main purpose in a region of low seismicity. In a region of moderate seismicity, seismic isolation may serve the both purposes: the reduction of seismic load and the standardization of seismic design.

(5) Determination of the Allowable Displacement Limit of the Seismic Isolation Device

- The allowable displacement limit of the seismic isolation device may be determined using either of the following methods:
  (i) Determination based on ultimate displacement of the seismic isolation device or crossover piping installed between seismic isolated building/equipment and non-isolated building/equipment.
  (ii) Determination based on satisfaction of the performance goals for core damage frequency and containment failure frequency evaluated by the risk assessment.

  In the past, the first method (i) has been used normally in the designing of seismic isolation structure. However, it is also possible to use the second method (ii) because, when a seismic isolation structure is applied, the response displacement of the seismic isolation device could be a virtual main cause of damages.

  Specifically, the methodology of seismic PSA can be used in the second method (ii).

(6) Input Ground motion for the base-Isolated Structure

- As a general rule, input ground motion for the response analysis of the base-isolated structure shall be obtained from earthquake transmission analysis utilizing the design basis ground motion.
- Considering that base-isolated structure has relatively low natural frequency, the design basis ground motion is required to contain low frequency components. In terms of the earthquake transmission analysis, the reviewer should check the filtering effect for those components not to reduce conservativeness of design condition.

(7) Method Used in the Analysis of Seismic Response of Base-isolated Structure

- When the seismic isolation structure is implemented, the method used in the analysis of seismic response of building and equipment shall be as follows, as a general rule:

	Seismic Response Analysis of Building	Seismic Response Analysis of Equipment in Building
Building Isolation	Time history analysis	With Equipment isolation: Time history analysis Without Equipment Isolation: Time historical analysis Response spectrum analysis
Equipment Isolation	N/A-	Time history analysis

4.2 Basic Policy Concerning the Implementation of Seismic Isolation Structure

- Base-Isolated structures shall be as seismically safe and reliable as aseismic structures.
- Base-isolated structures shall be designed to comply with provisions in the New Regulatory Requirements for Light Water Nuclear Power Plants (hereinafter “New Rules”), as a general rule.
- Base-isolated structures have a long natural period and therefore differ from aseismic nuclear facilities in their characteristics of response to ground motion. If using design methods different from those described in the Seismic Guide is adequate to reflect those characteristics in design, design methods may be changed in case where the reason for doing that is clearly stated.
- If the design method based on the New Rules is likely to compound the risk of seismic isolated facilities, an appropriate design policy should be introduced.

(Commentary)

- When a seismic isolation structure is implemented, the natural period of the superstructure is longer than that of aseismic structures. Apart from that, however, the philosophy of seismic design does not differ much between seismic isolation structures and aseismic structures.
- Therefore, seismic isolation structures shall also be designed to comply with provisions in the New Regulatory Requirements for Light Water Nuclear Power Plants established by Nuclear Regulation Authority (NRA), as a general rule.
- Since the basic aim of the seismic isolation structure is to reduce dynamic energy of earthquake by the seismic isolation device, the seismic safety of seismic isolation structure depends on its dynamic behavior during earthquake. Therefore, a sufficient safety margin shall be provided when defining the design basis ground motion and when designing the seismic isolation equipment, for example.

  Moreover, effort must be made to make the residual risk as small as practicable.

5. Review on Seismic Design Stage

5.1 Classification of Seismic Importance

- The seismic classification of seismic isolation device shall be categorized in the same class of the superstructure. In addition, the following definition shall apply:
  - Building isolation
    The seismic isolation device shall be regarded as an indirect support structure.
  - Equipment isolation
    The seismic isolation device shall be regarded as a direct support structure (in the category of "other support structures") for the supported components.
- It is necessary to consider a possibility that damage of low classification facilities would affect high classification facilities.

(Commentary)

(1) Seismic Classification of Seismic Isolation Device for Building Isolation

- In the case of building isolation, the seismic isolation device, positioned between the superstructure and substructure, has a function to support the building.
- In this case, the seismic isolation device falls into the category of "indirect support structure" according to the Technical Code for Seismic Design of Nuclear Power Plants (JEAC4601-2008): "structure made of reinforced concrete, steel frame or the like bearing the load transmitted from direct support structure."
- The seismic isolation device, therefore, shall be regarded as an indirect support structure.

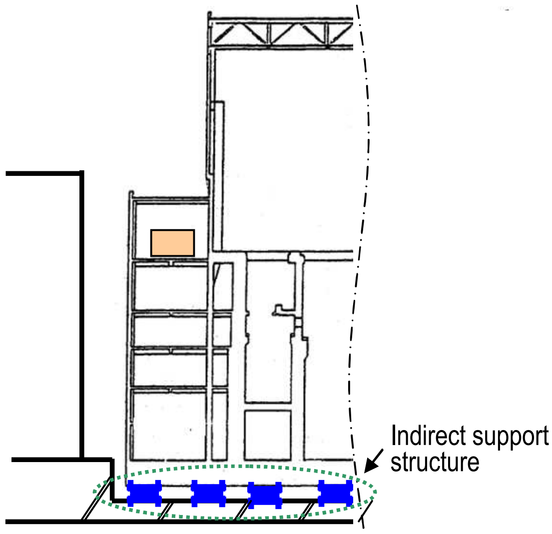


Fig. 5.1-1 Seismic classification of seismic isolation equipment for building isolation

(2) Seismic Classification of Seismic Isolation Device for Equipment Isolation

- The following statement is found in the JEAC4601-2008 with regards the "definition of facilities" under the classification of seismic importance: "The term 'main facilities' refers to those facilities which are directly related with the given function, while the term 'auxiliary facilities' refers to those facilities that assist the functioning of main facilities." The seismic isolation device does not fall into the category of either main facilities or auxiliary facilities.
- Again in the JEAC4601-2008, direct support structures are defined as "structures that are attached directly to main or auxiliary facilities, or directly bear the weight of them."

The seismic isolation device, therefore, shall be regarded as a direct support structure for the supported equipment.

- Direct support structures fall into two categories: “support structures defined in Rules on Design and Construction for Nuclear Plant (JSME S NC1-2001)” and “other support structures.” Examples of both are found in the JEAC4601-2008.
- Looking at the seismic isolation structure from the viewpoint presented in the JEAC4601-2008, it should be appropriate to regard that the support structure (excluding foundation bolts) that exists above the seismic isolation device and supports main equipment, etc. among superstructure falls into the category of “support structures defined in JSME S NC1-2001” while the seismic isolation device falls into the category of “other support structures.”
- As a conclusion from the above, the seismic isolation device shall be fall into same classification of seismic importance with the isolated equipment, and it shall be regarded as a direct support structure for the superstructure (other support structures).

(3) Consideration of Influence of Damage

- It is possible that facilities in low seismic classification would be damaged by earthquake and would affect facilities in high seismic classification. When classifying the seismic isolation structure, the possibility of the influence on facilities that are rated in the high classification should be considered, noting unique characteristics of base-isolated structures such as their large response displacements during earthquake.

(Points Requiring Attention on Review)

- Confirm the seismic classification of the superstructure and substructure.
- Confirm the seismic classification of the seismic isolation device.
- Is the seismic classification of the superstructure and substructure in harmony with the seismic classification of the seismic isolation device?
- Is the possibility of influence of damage on surrounding facilities considered when applying the seismic classification system?

5.2 Design Basis Ground Motion

- The design basis ground motion used in the design of the base-isolated structure (hereinafter "input ground motion") must be determined appropriately in consideration of differences of seismicity (high, moderate or low) around the site and differences of horizontal and vertical ground motions.
- As a general rule, input ground motion shall be obtained from earthquake transmission analysis utilizing the design basis ground motion.

(1) Differences of Seismicity

1) High Seismicity Region

Even though the design basis ground motion Ss as defined in the New Rules may be applicable, sufficient consideration to use the conventional Ss, which is for non-isolated structure, is needed because a seismic isolation structure generally has a relatively long natural period. Therefore, its validity as the design basis ground motion for a seismic isolation structure shall be checked with attention to the points described in the section (2), and the design basis ground motion must be newly created if necessary.

2) Moderate Seismicity Region

The same instruction as above [1) High Seismicity Region] shall apply.

Considering the medium level of seismicity, two or more sites may share the same design basis ground motion.

In that case, the shared design basis ground motion shall be conservative enough to be able to serve as a representative design basis ground motion applicable to multiple sites.

3) Low Seismicity Region

The same instruction as above [2) Moderate Seismicity Region] shall apply.

Considering the low level of seismicity, it shall be allowed to prepare and use an internationally agreed design basis ground motion.

(2) Differences of Directions of Ground Motions

The following provisions concerning differences of horizontal and vertical ground motions shall apply to all three cases described above that address differences of seismicity.

1) Horizontal Ground Motion

Considering that a seismic isolation structure has a relatively long natural period (usually between 2.0s and 5.0s), proper attention must be given to longer period components in the design basis ground motion.

2) Vertical Ground Motion

When the vertical seismic isolation is installed, the natural period in the vertical direction usually ranges from 0.5s to 1.5s. In that case, it is possible to use the design basis ground motion defined in the New Rules. If the vertical natural period largely exceeds 1.5s due to the configuration of the seismic isolation device, for example, it is necessary to reevaluate, like in the case of 1) above, giving attention to the longer natural period.

(Commentary)

(1) Differences of Seismicity

1) High Seismicity Region

The New Rules demands the consideration of ground motions with specified source like active faults near the site, and ground motions postulated with no specified source. The New Rules provides a necessary and sufficient set of requirements concerning seismic design. Even in the design of seismic isolation structures, the design basis ground motion determined according to provisions in the New Rules remains valid.

However, considering that the seismic isolation structure has a relatively longer natural period, the design basis ground motion for the seismic isolation structure should include longer period components, and the input ground motion also must be newly created if necessary.

2) Moderate Seismicity Region

The concept of design basis ground motion for the seismic isolation structure remains the same regardless of regional differences of seismicity. Therefore, the instruction concerning the determination of design basis ground motion for “1) High seismicity Region” is equally applicable to implementations in a region of moderate seismicity.

Since the implementation of the seismic isolation structure enables significant reduction of seismic load, a standard design basis ground motion can be provided to promote the standardization of seismic design.

Considering that, the Guidelines allow the preparation of a common design basis ground motion for use at multiple sites. In that case, the shared design basis ground motion shall be conservative enough to be able to serve as a representative design basis ground motion applicable to multiple sites.

3) Low Seismicity Region

The same consideration as above "2) Moderate Seismicity Region" shall apply.

Considering that sites of low seismicity are found mostly outside Japan, the Guidelines allows the preparation and use of an internationally agreed design basis ground motion. Again in this case, the shared design basis ground motion needs to be sufficiently conservative.

(2) Differences of Directions of Ground Motions

The following provisions concerning differences of horizontal and vertical ground motions shall apply to all three cases described above that address differences of seismicity.

1) Horizontal Ground Motion

- The design basis ground motion Ss shall be defined in pursuant to provisions in the

New Rules, in consideration of both ground motions with specified source (ground motions derived from fault models and response spectrum) and ground motions with no specified source.

- Considering that the seismic isolation structure has a relatively long natural period (usually between 2.0s and 5.0s), the design basis ground motion must sufficiently include longer period components that is required in the design of the seismic isolation structure.
  In the determination of the design basis ground motion, it is similarly important to give attention to the possibility of a great earthquake at a distant location, which is going to induce longer period vibration.
- Considering that the seismic isolation structure has a relatively long natural period, the design basis ground motion shall have sufficient duration time.
- In the determination of the design basis ground motion Ss, attention must be given to factors that may influence long period components of the ground motion: active faults near the site, distant earthquake, deep soil structure affecting the propagation route characteristics, etc.
- If observation records of ground motions with long period components are available, it is advisable to use such records to supplement the design basis ground motion determined by the procedure described above.

2) Vertical Ground Motion

- Seismic isolation in the vertical direction differs from that in the horizontal direction because of the necessity to support the dead weight. This gives rise to the following characteristics:
  (i) An excessively long natural period in the vertical direction causes difficulty in supporting the dead weight.
  (ii) It may also make the structure more prone to rocking motion.
  Therefore, the natural period in the vertical direction is usually designed to range approximately between 0.5s and 1.5s. In the case of vertical seismic isolation, attention should be paid to the fact that available period range is limited.
- Resonance of the base-isolated structure shall be investigated because vertical ground motions whose dominant period components were included in period range above were observed.
- In the case where the vertical natural period of the base-isolated structure is relatively long (largely exceeds 1.5s), attention should be paid to supporting function of the superstructure.
- In the case where the vertical natural period is shorter than 0.5s, attention should be paid to decrease of isolation effect.
- Vertical natural period of the base-isolated structure is limited between 0.5s and 1.5s. Since vertical ground motion whose dominant period components were included in this

range was observed at Taiwan Chi-Chi Earthquake, attention shall be paid to the resonance of the superstructure. However, response acceleration due to the resonance could be suppressed by countermeasures such as increase of damping factor and so on.

(3) Supplementary Information

- If any referential ground motion for use in the design of seismic isolation structure is defined independently of the New Rules, the utility shall provide clear explanations about the method by which the ground motion was determined and about its validity.

(Points Requiring Attention on Review)

- Confirm that the design basis ground motion includes the relatively longer period components that affect the response of base-isolated structure.
- If it is deemed that long period components included in the design basis ground motion Ss is not enough to design the base-isolated structure, confirm that an appropriate measure has been taken. For example, a referential ground motion which includes longer period components (based on observation data collected at the site, for example) is used in design in addition to the Ss.
- Check the duration time of the design basis ground motion.
- If the same design basis ground motion is shared by multiple sites, confirm the reasonability of the use.

5.3 Basic Performance Requirements for Seismic Isolation Device

The seismic isolation device shall be capable of supporting, restoring and damping, and shall stably maintain these functions at a satisfactory level throughout the in-service period. In the case where a stopper is installed into the seismic isolation device, the stopper shall not affect the function of the seismic isolation device. The evaluation of these functions differs according to regional differences of seismicity (classified as high, moderate and low).

(1) High Seismicity Region

1) Supporting Function

- The seismic isolation device shall be capable of stably supporting the superstructure in the presence of vertical load (in normal state, during earthquake and after earthquake). The quantity of relative displacement in the vertical direction shall not differ significantly among the dead weight supporting devices.
- The seismic isolation device shall be capable of stably supporting the superstructure in spite of changes in the axial force due to the horizontal deformation during earthquake.

2) Restoring Function

- The seismic isolation device shall be able to exert a restoring force against the design seismic force derived from the design basis ground motion with adequate safety margin.
- The seismic isolation device shall tolerate deformation, with sufficient safety margin, up to the allowable displacement limit.

  The allowable displacement limit of the seismic isolation device may be determined using either one of the following two methods:

  (i) Determination from the ultimate displacement of the seismic isolation device or the crossover piping that connects between base-isolated building/equipment and non-isolated building/equipment.

  (ii) Determination from the viewpoint of satisfying performance goals for core damage frequency and containment failure frequency based on the risk assessment.

3) Damping Function

- The seismic isolation device shall have sufficient damping capability corresponding to the characteristics of the device.

4) Stopper Function

- There shall be enough clearance between the seismic isolation device and the excessive displacement stopper so that the function of the seismic isolation device would be kept.

(2) Moderate Seismicity Region

The basic performance requirements for seismic isolation device implemented in a moderate seismicity region shall be similar to the requirements described above for "1) High Seismicity Region."

(3) Low Seismicity Region

The basic performance requirements for seismic isolation device implemented in a low seismicity region shall be similar to the requirements described above for "1) High Seismicity Region."

(Commentary)

(1) High Seismicity Region

1) Supporting Function

Seismic isolation devices that concern the supporting function fall into two major groups: laminated rubber bearings and rolling/sliding bearings.

As a general rule, the seismic isolation device shall use only those which have gained the approval of the Minister of Land, Infrastructure, Transport and Tourism on seismic isolation materials.

(i) Laminated Rubber Bearings

- Since the deformation of laminated rubber bearings during earthquake may affect the supporting function, it is required, in the design stage, to appropriately determine the design strength limit of compression with a view to maintaining the supporting function in spite of the anticipated horizontal deformation during earthquake.
- As a general rule, laminated rubber bearings shall sustain compressive force both in the normal state and during earthquake. If any of the laminated rubber bearings may be subject to tensile force during earthquake due to rocking motion, it shall be verified that the bearings will not lose the supporting function in the presence of the anticipated horizontal deformation by test or analysis.
- Since the relationship between the compression limit load and the shearing limit displacement differs from product to product, it is necessary, in the design stage, to understand the conditions and other details of product test on which the manufacturer of laminated rubber determines the critical horizontal deformation, and the utilities shall determine the design contact pressure and deformation range in consideration of the guaranteed performance of laminated rubber.

(ii) Rolling/Sliding Bearings

- The bearings shall be able to maintain the supporting function by withstanding the earthquake load as well as the compressive load that they sustain over a long period of time.

- Rolling and sliding bearings produce frictions, which influence the behavior of seismic isolation structure during earthquake.
  It is necessary, therefore, to give attention to how frictions may influence the response of seismic isolation structure
- If any of the rolling/sliding bearings may be subject to tensile force during earthquake, it shall be verified that bearings will not lose supporting function by test or analysis.
- Since dust in the rolling/sliding bearings would affect function of the device, appropriate cover such as dustproof cover shall be applied. In the case of applying dustproof cover, it is necessary to give attention to influence of the cover on the motion of the bearing.

2) Restoring Function

a. Basic performance requirements

Seismic isolation devices that concern the restoring function fall into two major groups: laminated rubber bearings and springs.

(i) Laminated Rubber Bearings

- In the high strain region, laminated rubber hardens and then breaks.
  According to descriptions in "JSSI Criteria, Manual and Examples for the Designing of Seismic Isolation Applied Buildings with Time Historical Analysis," hardening begins when shearing strain reaches the level of from 200% to 250%. In the design stage, it is necessary to ensure that laminated rubber is used within a generally linear region without the hardening, as a general rule. If laminated rubber is to be used beyond the range of linearity, it is necessary to ensure that its nonlinear characteristics are well understood.
- Laminated rubber bearings may be subject to tensile force derived from vertical ground motion. When designing laminated rubber bearings, it is necessary to determine the design horizontal displacement in consideration of the relationship between horizontal displacement and yield load in the presence of tensile load.

(ii) Springs

- The allowable displacement limit for springs is often determined by the range of motion. It is assumed that the displacement produced during earthquake rarely exceeds the range of elastic deformation of spring.
- However, for the sake of assurance, considering that there have been so far only a limited number of cases of a seismic isolation structure implemented at nuclear facilities, the Guidelines demand to confirm that the response displacement of spring satisfies not only the allowable displacement limit but also the range of elastic deformation.
- The above provision is meant to ensure that displacement during earthquake does

not exceed the range of elastic deformation of spring, and is not meant to discourage the implementation of seismic isolation device that is deliberately designed to have nonlinear response characteristics (by the addition of trigger, for example).

b. Determination of the Allowable Displacement Limit

The allowable displacement limit mentioned above can be determined by either one of the following two methods:

(i) Determination from the ultimate displacement of the seismic isolation device or the crossover piping that connects between base-isolated building/equipment and non-isolated building/equipment.

(ii) Determination from the viewpoint of satisfying performance goals for core damage frequency and containment failure frequency based on the risk assessment.

The first method (i) has been used normally in the design of seismic isolation structure. However, it is also possible to use the second method (ii) because, when a seismic isolation structure is applied, the excessive displacement of the seismic isolation device is virtually the dominant cause of damages. Specifically, the methodology of seismic PSA can be used to implement the second method (ii).

See Section 5.6 for details of how to determine the allowable displacement limit.

3) Damping Function

Seismic isolation devices that concern the damping function fall into three major groups: hysteretic dampers, fluid dampers and friction dampers.

(i) Hysteretic Damper

- Examples of hysteretic dampers include steel-rod dampers.
- Hysteretic dampers shall maintain the function of damping good enough to be able to cope with the maximum allowable displacement and the allowable cumulative deformation.

(ii) Fluid Damper

- Examples of fluid dampers include oil dampers and viscous dampers.
- Fluid dampers shall maintain the function of damping good enough to be able to cope with the maximum allowable displacement and the maximum allowable velocity.

(iii) Friction Damper

- Friction dampers shall maintain the function of damping good enough to be able to cope with the maximum allowable displacement.

(2) Moderate Seismicity Region

The basic performance requirements for seismic isolation devise implemented in a region of moderate seismicity shall be similar to the requirements described above for “(1) High Seismicity Region”.

(3) Low Seismicity Region

The basic performance requirements for seismic isolation device implemented in a region of low seismicity shall be similar to the requirements described above for “(1) High Seismicity Region”.

(Points Requiring Attention on Review)

(1) Supporting Function

- Check the range of motion of the device and whether the design displacement is within the range of motion of the seismic isolation device.
- When the laminated rubber bearings are used, examine the relationship between the compression limit load and the shearing limit displacement. Check whether the design displacement is consistent with the ultimate displacement.
- When the rolling/sliding supports are used, confirm their friction coefficient and whether the frictions are considered in the earthquake response analysis.
- Check whether the supporting function is maintained in the case of presence of tensile force. Investigate the method used in the verification concerning the maintenance of supporting function.

(2) Restoring Function

- Check whether the allowable displacement limit is within the range of linearity.
- Check the range of motion of the device and whether the allowable displacement limit is within the range of motion of the seismic isolation device.
- When the laminated rubber bearings are used, check whether the allowable displacement limit is smaller than the displacements at which the hardening or fracture takes place.

(3) Damping Function

- Confirm the coefficient of damping.
- Check whether the damping devices maintain their damping function up to design limit.

(4) Excessive Displacement Stopper and Dustproof Cover

- Investigate the influences of the excessive displacement stopper and dustproof cover on the seismic isolation function.

5.4 Design Policy of Base-Isolated Structure

In the design of the base-isolated structures, it is possible, as a general rule, to make use of conventional design methods for non-isolated structures such as those described in the Technical Code for Seismic Design of Nuclear Power Plants (JEAC4601-2008).

However, base-isolated structures differ from non-isolated structures in vibration characteristics because they have a relatively longer natural period. The design methods for seismic isolation structures must take into account such differences. This section describes design policy considerations unique to base-isolated structures.

(1) Input Ground Motion

- In the case of building isolation, the input wave obtained from earthquake transmission analysis utilizing the design basis ground motion is a ground motion at the base mat of the substructure. Appropriate analysis method should be selected considering structure and property of the soil in which the earthquake transmits.

  In the case of equipment isolation inside a building, seismic response analysis of building is conducted to obtain the response of substructure or the floor on which the equipment isolation is installed and take the response wave by the analysis as the input wave to the equipment isolation. In the case of outdoor equipment isolation, seismic response analysis of soil is conducted to obtain the response of the substructure and take the response wave by the analysis as the input wave to the equipment isolation.

(2) Evaluation of the Basic Performance of Seismic Isolation Device

The seismic isolation device shall stably maintain the required functions (supporting, restoring and damping functions) at a satisfactory level throughout the in-service period. See Section 5.3 for detailed discussions on this subject.

(3) Design Basis Seismic Force

- The dynamic seismic force defined in the New Rules shall be referred to in the design of base-isolated structure.
- In the calculation of the dynamic seismic force, the designer shall use an appropriate ground motion according to seismic classification of structure/component, and it shall be based on the design basis ground motion Ss or another ground motion. (See Section 5.2.)
- In the determination of the design basis seismic force, it shall be ensured that the seismic force corresponding to dominant natural period band of the base-isolated structure is not lower than that for base-isolated structures implemented in non-nuclear facilities.

(4) Seismic Response Analysis Method

- As a general rule, the seismic response analysis of base-isolated structures shall be conducted using the time history analysis. A different method of seismic response analysis can be used, provided that its validity is demonstrated.

(5) Seismic Response Analysis Model

- It is necessary to use an appropriate seismic response analysis model that properly simulates the vibration characteristics of the seismic isolation device.

(6) Seismic Isolation Element Characteristics for Seismic Response Analysis

- The characteristic values of the seismic isolation element for seismic response analysis must be determined in consideration of the service environment, etc.
- Upon the completion of seismic isolation elements for actual implementation, the characteristics such as stiffness and damping factor shall be evaluated by testing all products, as a general rule, in order to confirm the validity of the seismic isolation element characteristics used in seismic response analysis.

  The above provision shall not apply if testing up to the design condition may cause change of design property (e.g. plasticity of steel bar damper). In that case, the validity of the seismic isolation element characteristic values used in seismic response analysis can be confirmed by feasible testing and combining the test result with analysis, etc.

  A similar adjustment is allowed when testing is difficult for certain seismic isolation element due to their large size. If total inspection for the elements is deemed unnecessary because the dispersion of seismic isolation element characteristic values among products is evidently so small that it cannot affect the result of seismic response analysis of seismic isolation structure, it can be substituted by sampling inspection, provided that its validity is demonstrated.

(7) Combination of Horizontal and Vertical Seismic Loads

- The combination of horizontal and vertical seismic loads shall be addressed by an appropriate method in consideration of the characteristics of the seismic isolation structure.
- Coupling behavior of vertical seismic force caused by rocking motion due to horizontal ground motion and vertical ground motion should be considered.

(8) Other Considerations

The following describes other topics that require consideration.

- There is a wide variety of seismic isolation devices and the topics requiring consideration depends on the configuration of the device. In designing a seismic isolation structure, therefore, topics requiring consideration have to be determined for every seismic isolation device.
- In the case of design of excessive displacement stopper and dustproof cover, influences on the seismic isolation function should be considered.

(Considerations common to building isolation and equipment isolation)

1) Offset of the center of rigidity and the center of gravity

- A large distance between the center of rigidity and the center of gravity leads to a rotational movement during earthquake, which may cause inconveniencies such as the increase of relative displacement during earthquake. Therefore, care must be taken to make its center of rigidity and its center of gravity positioned as close together as possible.
- If there is a large distance between the center of rigidity and the center of gravity, it shall be ensured that the seismic isolation device is able to provide the required seismic isolation functions. Hereinafter, “the required seismic isolation functions” mean the functions described in Section 4.2 “Basic Policy Concerning the Implementation of Seismic Isolation Structure”.

2) Consideration of rocking motion during earthquake

- The seismic isolation device shall be able to provide the required seismic isolation functions even in the presence of rocking motion.

3) Consideration of variation in the performance of seismic isolation device

○Dispersion of seismic isolation element characteristics

- The seismic isolation device shall be able to provide the required seismic isolation functions even in the presence of dispersion of characteristics of seismic isolation elements (rigid elements, damper elements, etc.), including other influences such as aging, temperature changes and so on.

○Changes of seismic isolation functions during earthquake

- The seismic isolation device shall be able to provide the required seismic isolation functions even though the characteristics of seismic isolation elements go through changes while the seismic isolation structure moves during earthquake.

○ Changes in seismic isolation functions due to external events other than earthquakes

- When implementing the seismic isolation structure, it is also important to ensure protection against external events other than earthquakes by taking measures as required.

  The followings are examples of external events:
  - -- Strong wind
  - -- Lightening
  - -- Tsunami and flood
  - -- Slope slide due to earthquake
  - -- Fire

4) Seismic safety of facilities unique to seismic isolation structure

- As a result of implementing the seismic isolation structure, seismic risks of certain facilities may increase. Such facilities shall be clearly identified and it shall be demonstrated that they still retain seismic safety.

The followings are examples of such facilities:

- Crossover piping, etc., components installed between building/equipment and non-isolated building/equipment (See Section 5.5)
- Facilities in which sloshing shall be taken into account

(Considerations for building isolation)

1) Seismic safety of structures unique to building isolation

- The structures unique to building isolation (pedestal, etc.) shall be as safe as the rest of the base-isolated structure.
- The surrounding wall which is constructed between the building and surrounding soil shall be designed in such a manner that its collapsing does not affect the function of seismic isolation structure.

(Considerations for equipment isolation)

1) Variation of seismic isolation characteristics depending on the direction of seismic load input

- The seismic isolation device shall be able to provide the required seismic isolation functions irrespective of the direction of seismic load input.

2) Response characteristics depending on the configuration of the seismic isolation device

- Some kinds of seismic isolation devices have vibration characteristics of inducing nonlinear seismic response. The seismic isolation device shall be able to provide the required seismic isolation functions irrespective of kind of device.

(Commentary)

- Design methods for base-isolated structures shall take into account the long natural period of the structures.
- The seismic isolation equipment is composed of many elements such as laminated rubber bearings, springs, dampers, steel frame and foundation bolts.

  Therefore, when evaluating the structural integrity of base-isolated structure against earthquakes, estimating cause of failure and critical parts related to the failure shall be conducted, and appropriate methods for strength assessment and function maintainability assessment shall be chosen.

  The following are examples of failure mode:

  -- Fracture of crossover piping, etc.

  -- Large deformation or structural damage of restoring mechanism

  -- Loss of function of supporting element

  -- Loss of function of damping element

  -- Displacement of base-isolated structure larger than clearance (collision with surrounding structures)

-- Largely increased plasticity of the superstructure

-- Loss of vertical supporting function of the substructure

- Considering the above, this section describes typical topics requiring consideration, which are unique to seismic isolation structures.

  Since the response characteristics of base-isolated structure depends on the configuration of seismic isolation device, the topics requiring consideration shall be evaluated by type of the seismic isolation device which is installed to the seismic isolation structure.

(1) Determination of the Input Ground Motion

The determination of input ground motion to the seismic isolation structure can be done using the same methods that have conventionally been used in seismic design.

(2) Evaluation of the Basic Performance of Seismic Isolation Device

The seismic isolation device shall stably maintain the required functions (supporting, restoring and damping functions) throughout the in-service period.

See Section 5.3 for detailed discussions on this subject.

(3) Design Basis Seismic Force

○ Dynamic seismic force

- See below for the relationship between the classification of seismic importance and the design basis ground motion.

  When determining the design basis ground motion, it shall be noted that base-isolated structures have a relatively long natural period. See Section 5.2 for details.

  - Class S: Use the design basis ground motion Ss, which includes long period components if needed.
  - Class B: Following instructions in the New Rules, one may use 1/2 x Sd (Sd: ground motion for elastic design). When using 1/2 x Sd, however, one must demonstrate the reasonability of using it for seismic design in consideration of the characteristics of Sd. Sd is obtained by multiplying Ss by a factor designated as α, which should be equal to or larger than 1/2. When determining the value of α, it must be ensured that the level of 1/2 x Sd is not lower than the input ground motion used in the design of base-isolated structures for non-nuclear generic facilities.
  - Class C: It is allowed to apply design standards for seismic isolation structures for non-nuclear generic facilities.

(4) Seismic Response Analysis Method

- Seismic response analysis shall be conducted using the time history analysis, as a general rule. It is allowed to use a seismic response analysis method other than the time history analysis, provided that the validity of the chosen method is demonstrated.

(5) Seismic Response Analysis Model

- Since the seismic isolation device can have a wide variety of configuration, it is necessary to use an appropriate seismic response analysis model that properly simulates the vibration characteristics of the seismic isolation device to be used.

(6) Seismic Isolation Element Characteristics for Seismic Response Analysis

- The determination of seismic isolation element characteristics for seismic response analysis requires the consideration of service conditions, taking note that seismic isolation elements would be placed under severe condition in the case of equipment isolation.
- When the seismic isolation device is designed, the actual characteristics (spring stiffness and damping ratio, for example) of them have not been confirmed. Therefore, upon the completion of seismic isolation elements for actual implementation, all of them, as a general rule, shall be subjected to product testing for the determination of characteristic values, which should be compared with design values for the purpose of demonstrating the validity of design.

  If total inspection for the elements is deemed unnecessary because the dispersion of seismic isolation element characteristic values among products is evidently so small that it cannot affect the result of seismic response analysis of seismic isolation structure, it can be substituted by sampling inspection, provided that its validity is demonstrated.
- Judging validity of seismic isolation element characteristics for design depends on whether or not the differences between the assumed and measured values are so small that they do not affect seismic isolation functions.
- If the differences between the two above are so large that they may affect designed performance of the seismic isolation structure, seismic response analysis shall be newly conducted using the measured values of seismic isolation elements in order to confirm the availability of required seismic isolation functions.
- Depending on the type of seismic isolation elements, testing of the actual product up to the design condition may be difficult. (For example, testing a steel rod damper under the design seismic load is going to cause plastic deformation.) Moreover, the building isolation may involve the use of 1,000 ton-class laminated rubber bearings, which may be too large to be tested, or at least the testing of all of them may be difficult.

  In that case, the validity of the seismic isolation element characteristics used in seismic response analysis can be confirmed by combining practicable test with different specimens and analysis.

(7) Combination of Horizontal and Vertical Seismic Loads

- The combination of horizontal and vertical seismic loads shall be addressed by an appropriate method in consideration of the characteristics of the seismic isolation structure.
- In the case of horizontal seismic isolation, the base-isolated structure has a relatively long natural period in the horizontal direction while a vertical natural period is short, and therefore maximum responses in horizontal and vertical directions are likely to take

place simultaneously.

- When addressing the combination of horizontal and vertical seismic loads in the design of seismic isolation structures, the use of the Square Root of Sum of Squires (SRSS) method as in the design of non-isolated structures may result in non-conservative estimations (i.e. lesser safety margin).
- Therefore, an appropriate method, such as taking the sum of absolute values, taking the algebraic sum of the time history of seismic load in the horizontal and vertical directions, and horizontal/vertical simultaneous input analysis, shall be chosen in consideration of the characteristics of the seismic isolation structure.
- It is necessary to evaluate whether the coupling behavior of vertical seismic force caused by rocking motion due to horizontal ground motion and vertical ground motion would take place.
- A combination method like SRSS may be used neglecting the coupling behavior mentioned above if it is well justified by a reason such as that peaks do not overlap or synchronize between horizontal and vertical ground motions.
- Depending on the configuration of seismic isolation elements, it will be necessary to consider the combination of seismic loads in two horizontal directions. The combination of seismic loads in two horizontal directions requires similar considerations described above.

(8) Other Considerations

(Considerations common to building isolation and equipment isolation)

1) Eccentricity of the rigidity center and the gravity center

- In the case of base-isolated structure, large distance between the center of rigidity and the center of gravity causes rotational movement during earthquake. The rotational movement increases the relative displacement of the seismic isolation structure, which may lead to troubles such as (i) collision with another structure nearby and (ii) worsening of stress to crossover piping, etc., due to excessive relative displacement.
- Therefore, when designing a seismic isolation structure, care must be taken to make its center of rigidity and its center of gravity positioned as close together as possible.
- If there is a large distance between the center of rigidity and the center of gravity, its impact on the behavior of the seismic isolation structure shall be evaluated by analysis or experiment, and it shall be ensured that the seismic isolation device is able to provide the required seismic isolation functions, and measures should be taken if needed.

2) Consideration of rocking motion during earthquake

- In the case where seismic isolation is provided in both horizontal and vertical directions, previous test data indicate that a rocking motion may take place depending on the structural design.
- Coupling behavior of vertical seismic force caused by rocking motion due to horizontal

ground motion and vertical ground motion should be noticed.

- It is necessary to study the impact of the rocking motion by analysis or experiment and demonstrate that the seismic isolation device is able to provide the required seismic isolation functions.

3) Consideration of variation in the performance of seismic isolation device

○ Variation in seismic isolation element characteristics

- The seismic isolation device is composed of rubber elements, spring elements, damper elements, etc. There is usually dispersion in the characteristics (spring stiffness, damping ratio, etc.) of these elements. Therefore, it shall be ensured in design that the seismic isolation device is able to provide the required seismic isolation functions in spite of dispersion of characteristics.
- Major causes of dispersion in characteristics of the seismic isolation element are as follows:
  -- Dispersion of characteristics by product
  -- Variation due to aging (particularly of rubber*)
    ∗: According to descriptions in "JSSI Criteria, Manual and Examples for the Designing of Seismic Isolation Applied Buildings with Time Historiy Analysis" (Japan Society of Seismic Isolation), the axial stiffness and shear stiffness of laminated rubber increases by about 10-20% and by about 10-15% respectively over the period of 60 years, and the equivalent damping factor of high damping laminated rubber decreases by about 10% over the period of 60 years.
  -- Variation due to installation
    Variation due to installation should be investigated by performance test of the seismic isolation system.

○ Changes in seismic isolation functions during earthquake

- It is necessary to identify the factors that cause changes of the characteristics of seismic isolation elements during earthquake and estimate the magnitude of changes, and to ensure that the seismic isolation device is able to provide the required seismic isolation functions in spite of such changes.
- Factors that cause changes to the characteristics of seismic isolation elements depend on the configuration of elements. The causes shall be identified and measures shall be taken considering the configuration of the seismic isolation elements.
  - Examples are given below.

    [Supporting mechanism]

    Ball bearings: change of the coefficient of friction

    (The coefficient of friction between ball bearings and base plate may change as ball bearings travel on the base plate during earthquake.)

    [Restoring mechanism]

    Laminated rubber: dependency on contact pressure and temperature

[Damping mechanism]

Hysteretic damper: dependency on velocity and frequency

Fluidic damper: dependency on velocity, frequency and temperature

Friction damper: change of the coefficient of friction

○ **Changes in seismic isolation functions due to external events other than quakes**

(i) Measures against strong wind

Take measures as required even though it is believed that the wind load hardly affects the response of seismic isolation structures.

(ii) Measures against lightening

If laminated rubber is used in the seismic isolation devices, lightening protection measures must been taken because the rubber electrically isolates the building from the ground.

For protection against lightening, take measures such as electrical connection between the superstructure and substructure across the laminated rubber to prevent the occurrence of any major potential difference.

Ground cables shall be given a sufficient additional length to be able to allow the relative displacement of the seismic isolation structure during earthquake.

(iii) Measures against tsunami and flood

- Quake and tsunami may arise simultaneously but they rarely hit the site at the same time because they travel at different speeds. Nevertheless, considering the risk of aftershocks, the seismic isolation device shall be designed to maintain its functions even after being hit by tsunami.
- As protection against tsunami, measures such as sea wall are desirable to prevent the inflow of seawater into the area in which the seismic isolation device installed, but it shall be allowed to rely on different measures as long as there is an assurance that the seismic isolation device can maintain its functions. When planning measures, the prevention of drenching of electrical components by the penetration of seawater should be ensured particularly in the case of equipment isolation.
- Since one cannot deny the possibility of tsunami height beyond design basis, effort must be taken to make the residual risk as small as practicable.
- Protection against flood shall be similar to protection against tsunami.

(iv) Measures against slope slide due to earthquake

Measures shall be taken to ensure that slope slide due to earthquake does not harm seismic isolation functions. Safe distances from slope and landslide protection walls are examples of measures that can be taken.

(v) Fire protection

Measures shall be taken to ensure that fire caused by earthquake does not harm seismic isolation functions. For example, fire protection covers could be provided for laminated rubber bearings.

4) Seismic safety of facilities unique to seismic isolation

- Since the base-isolated facilities have a relatively long natural period, a certain kind of seismic response would increase. Such facilities shall be identified and their seismic safety shall be demonstrated.
  - -- Crossover piping, etc. that connects base-isolated building/equipment and non-isolated building/equipment. See Section 5.5 for details.
  - -- Facilities in which sloshing shall be taken into account
    Sloshing can be evaluated using conventional seismic design methods.

(Considerations for building isolation)

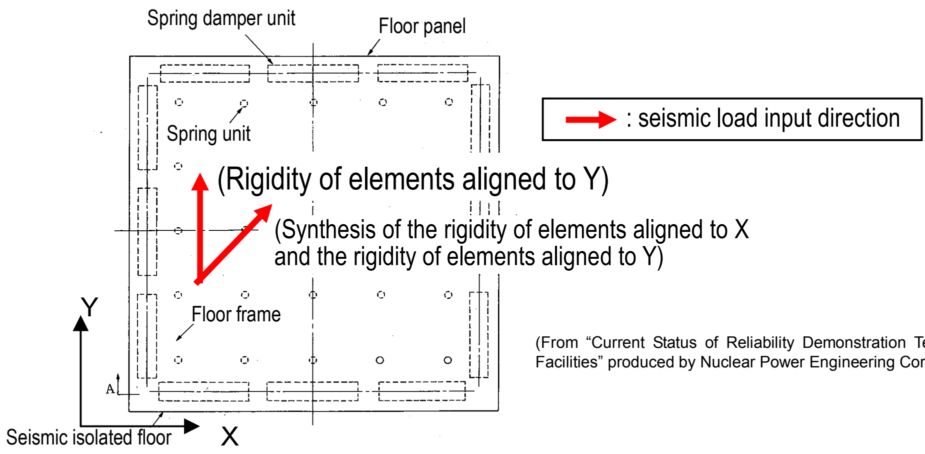
1) Seismic safety of structure/component unique to building isolation

- Some structures (pedestal, etc.) unique to seismic isolation structure may affect the functions of the base-isolated structure if they fail. Seismic safety of such structures, therefore, shall be as safe as the base-isolated structure.
- Surrounding walls shall have a level of seismic safety that is as good as that of the base-isolated structure. This provision is intended to prevent the fracture of surrounding walls leading to the loss of seismic isolation functions of seismic isolation structure; it shall not be interpreted as a demand on the safety function of surrounding walls themselves.
- As is the case with the surrounding walls, excessive displacement stopper is not required to have the safety function.

(Considerations for equipment isolation)

1) Variation of seismic isolation characteristics depending on the direction of seismic load input

- A certain kind of seismic isolation device may show different characteristics (e.g. stiffness) depending on the direction of seismic load input.
- In the case of spring-damper elements that can be used for equipment isolation, the stiffness in the parallel direction to element installation differs from the stiffness in the diagonal direction. As a result, the seismic isolation functions vary with the direction of seismic load input. (See Fig. 5.4-1)
- Therefore, it shall be ensured that such seismic isolation elements provide the required seismic isolation functions irrespective of the direction of seismic load input.
- Certain damper elements have also directional properties. When such damper elements are used, care must be taken to minimize the directional variation of seismic isolation characteristics.

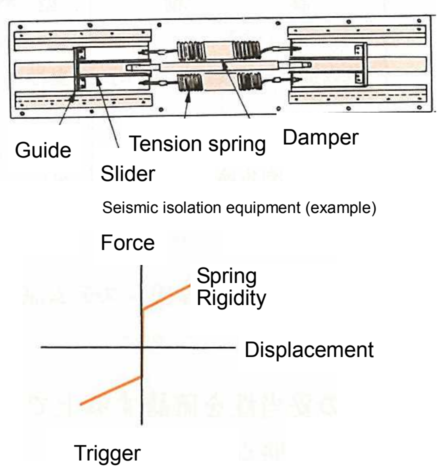


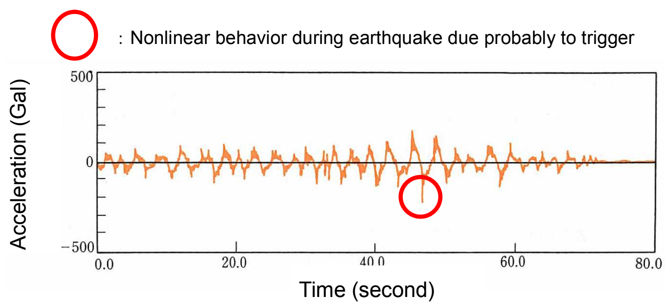
(From "Current Status of Reliability Demonstration Test of Nuclear Power Generation Facilities" produced by Nuclear Power Engineering Corporation in 1993)

Fig.5.4-1 Example of stiffness varying with the direction of seismic load input due to directional property of seismic isolation device

2) Response characteristics depending on the configuration of the seismic isolation device

- A certain kind of seismic isolation device may show some irregular behaviors (e.g. nonlinear behavior during earthquake caused by friction elements used as trigger or damper). (See Fig. 5.4-2)
- Therefore, when implementing a seismic isolation structure, attention shall be given to the characteristics of the seismic isolation device and it shall be ensured that the seismic isolation structure maintains the required functions in spite of such irregular behaviors.





Response of specimen on seismic isolated floor

Fig. 5.4-2 Example of nonlinear behavior due to trigger during earthquake

(Nuclear Power Engineering Corporation, "Current Status of Reliability Demonstration Test of Nuclear Power Generation Facilities", 1993)

(Points Requiring Attention on Review)

A wide variety of seismic isolation device would be available at nuclear power plants and the regulatory body must examine all cases of implementation applications submitted by utilities.

During the review, it shall be confirmed that the utility has evaluated probable failure mode of the seismic isolation structure and estimated critical parts related to the failure. It shall also be checked that the utility has chosen appropriate strength evaluation method and function maintainability evaluation method.

(1) Determination of the Design Basis Ground Motion and the Input Ground Motion

Basically, the determination of the design basis ground motion and the input ground motion to seismic isolation structure shall be according to conventional seismic design practices.

(2) Evaluation of the Basic Performance of Seismic Isolation Device

See Section 5.3 for detailed discussions on this subject.

(3) Design Basis Seismic Force

- Is the design basis seismic force rightly chosen corresponding to the seismic classification of the seismic isolation structure?
- Is the design basis ground motion higher than the ground motion for seismic design of seismic isolation structures for non-nuclear facilities?
- If 1/2 x Sd (Sd: the ground motion for elastic design) is referred to in the design of a Class B base-isolated structure, the reasonability of doing so shall be demonstrated.

(Reason of the need to demonstrate the validity of referring to 1/2 x Sd)

The Regulatory Guide for Reviewing Seismic Design prescribes that the design basis seismic motion Ss is used for the purpose of ensuring the seismic safety of facilities that are classified as Class S. Under this premise, the Regulatory Guide for Reviewing Seismic Design additionally defines the ground motion for elastic design Sd in order to improve the reliability of seismic design. Utilities are given the freedom to adjust the value of Sd to a certain extent: Sd = (α x Ss) where α should be equal to or larger than 1/2.

Therefore, it would be right to assume that the Regulatory Guide for Reviewing Seismic Design mentions that Sd is one of referential ground motion to be used in the seismic design of Class S facilities and it does not suggest that Sd can be used for the ensuring of seismic safety.

On the other hand, commentaries on Regulatory Guide for Reviewing Seismic Design describes that in the case where Class B facilities may resonate during earthquake, 1/2 x Sd can be referred to the evaluation of the those facilities.

Since the design basis ground motion for Class B facilities had been defined conventionally as 1/2 x S1, the above expression appears to have resulted simply from the substitution of S1 by Sd. However, considering the basic ideas given by the Regulatory Guide for Reviewing Seismic Design, it seems rather inappropriate to take 1/2x Sd as the sole ground motion for the seismic design to ensure the seismic safety of Class B facilities, more so because utilities have the freedom to adjust the level of Sd to a certain extent.

Considering the above, the Guidelines demand that, if 1/2 x Sd is referred to as the design basis ground motion for a seismic isolation structure that falls into the category of Class B facilities, the utility shall examine the reasonability of using 1/2 x Sd from the viewpoint of ensuring seismic safety. Utilities also can use other appropriate ground motion for design of Class B facilities as needed.

Sd is obtained by multiplying Ss by a factor designated as α that should be equal to or larger than 1/2. When determining the value of α, it must be ensured that the level of 1/2 x Sd is not lower than the ground motion used in the seismic design of base-isolated structures for non-nuclear facilities in the frequency range associated with the dominant period of the base-isolated structure. This rule is meant to ensure that the design basis ground motion for Class B facilities in seismic isolation structure does not become smaller than the design basis ground motion for Class C facilities.

(4) Seismic Response Analysis Method

- Is the validity of seismic response analysis method confirmed by testing? Have the methods been used for the seismic design of nuclear power plants?
- The regulatory body confirms the validity of those methods by having utilities submit the test results and simulation analysis results.

(5) Seismic Response Analysis Model

- The regulatory body confirms the validity of analysis models by having utilities submit the simulation analysis results and test results related to the analyses.

(6) Seismic Isolation Element Characteristics for Seismic Response Analysis

- It should be confirmed that the characteristics of individual seismic isolation elements used in the seismic response analysis are verified by the inspection of all of them (by product testing, performance testing on site, etc.)
  If not all products have been inspected or tested, or if products were tested without fully covering the design condition, have the utility explain the reason and demonstrate the validity of characteristics used in the seismic response analysis.
- If the seismic isolation element characteristics used in the design differ from the characteristics confirmed by the inspection of actual products, revised seismic response analysis and appropriate evaluation shall be conducted using the confirmed characteristic in order to ensure the availability of required seismic isolation functions.

(7) Combination of Horizontal and Vertical Seismic Loads

- Confirm the validity of the calculation method used for combining horizontal and vertical seismic loads.
  If an evidently conventional method (for greater safety margin), such as the sum of absolute values, is used, there is no need to confirm the validity of the method. If a method like the Square Root of Sum of Squires (SRSS) is used, require the utility to demonstrate the validity of the chosen method.
- This subject, titled “combination of horizontal and vertical seismic loads,” concerns the calculation method used for combining the horizontal and the vertical seismic load due to horizontal and vertical ground motion respectively.

(8) Other Considerations

(Considerations common to building isolation and equipment isolation)

1) Offset of the center of rigidity and the center of gravity

- Is it confirmed that the center of rigidity and the center of gravity are located so close that there is no risk of a large rotational movement? Did the utility evaluate the potential impact of such rotational movement on the relative displacement of the structure during earthquake?
- Since the evaluation above is normally done by analysis, require the utility to submit the analysis result. If the utility has evaluated the impact by another method, require the utility to report the method and result.

2) Consideration of rocking motion during earthquake

- Find out how large the rocking motion is expected in the case where three dimensional (both horizontal and vertical direction) seismic isolation is installed.
- Has the utility verified that the seismic isolation device maintains the required seismic isolation functions even in the presence of rocking motion?
- To make sure, require the utility to submit the analysis result. If the utility has relied on testing for verification, require the utility to submit the test result.

3) Consideration of variation in the performance of seismic isolation device

○ **Consideration of variation in seismic isolation element characteristics**

- Confirm that the utility has designed seismic isolation device considering the individual difference of products, dispersion caused by aging, dispersion data obtained from performance test on site and so on. (e.g. choosing characteristics that would result in conservative estimation, conducting analysis in consideration of the dispersion and designing the structure corresponding to the result of such estimation and analysis).

○ **Consideration of changes in seismic isolation functions during earthquake**

- Has the utility identified the factors that cause changes of characteristics of seismic isolation elements during earthquake and evaluated the extent of changes?
  Have these changes been considered in the seismic response analysis?
  Will the seismic isolation device maintain the required seismic isolation functions in

spite of these changes?

- **Consideration of changes in seismic isolation functions due to external event other than quakes**
  - What type of external events has the utility given attention to?
  - Confirm the reasonability of combination of earthquake and the given events referring historical records
  - Are the facilities designed to have a level of seismic safety that is good enough to be able to withstand the combining of the given events with earthquake?
  - Give particular attention to the combination of quake and tsunami because it is highly probable.
    It is particularly important to ensure protection against the risk of seawater or floating objects entering into seismic isolation area and disabling the seismic isolation functions against aftershocks or other events.

4) Seismic safety of facilities unique to seismic isolation structure

- Since the base-isolated facilities have a relatively long natural period, the seismic response, such as displacement, sloshing and so on, would increase. Such facilities shall be identified and it shall be ensured that they maintain the required level of seismic safety.

(Considerations for building isolation)

1) Seismic safety of structure/component unique to building isolation

- Are the structure/component unique to seismic isolation structure designed to have the required level of seismic safety?

(Considerations for equipment isolation)

1) Variation of seismic isolation characteristics depending on the direction of seismic load input

- With a certain type of seismic isolation device, seismic isolation characteristics vary with the direction of seismic load input and this variation may impact the seismic safety of the superstructure. Has the utility assessed this impact?
  Confirm whether there are any seismic isolation elements whose characteristics depend on direction of seismic load input.

2) Response characteristics depending on the configuration of the seismic isolation device

- A certain seismic isolation device, depending on its construction, may show nonlinear response during earthquake. Confirm whether such kind of seismic isolation device is installed.
- If there is any probability of irregular behavior, it shall be ensure that the seismic isolation device can maintain the required seismic isolation functions in spite of that. To

make sure, require the utility to submit the analysis result. If the utility has relied on testing for verification, require the test result.

3) Other considerations

- Confirm implementation of exposure test, storage condition of test result.
- Check the clearance gap between base-isolated structure/equipment and adjacent structure/component.
- In the case of equipment isolation, check the measurement against internal inundation such as draining trench, height of pedestal.

5.5 Interfaces between Base-Isolated Structure and Non-Isolated Structure

Compared with non-isolated structures, base-isolated structures respond to earthquake with greater displacements and therefore require the following considerations concerning the design of the interface between the base-isolated and non-isolated structures.

(1) Influences on Seismic Isolation Functions

- Piping, cables, floor and similar installations that connect between base-isolated and non-isolated building/equipment shall not have any significant influences on the seismic isolation functions of the seismic isolation structure.
- It shall be ensured that the base-isolated structure will not collide with other structure during earthquake.

(2) Maintaining the Integrity of Crossover Components Against Earthquake

- Crossover piping, etc. shall maintain their integrity against displacement caused by earthquake.

(Commentary)

(1) Influences on Seismic Isolation Functions

- Remembering that the base-isolated structure is displaced not only into a direction parallel to its edges but also into a diagonal direction during earthquake, it shall be ensured that there is a sufficiently large clearance between base-isolated and non-isolated structures, and also that there is no other structures within the range of motion of the base-isolated structure.
- It shall be ensured that there is no risk of a crossover piping or floor adversely affecting the seismic isolation functions.
- For example, concentrated installation of the crossover component would cause torsional motion of the base-isolated structure, and it is also possible that frictions due to the crossover component would constrain the motion of the base-isolated structure.

(2) Maintaining the Integrity of Crossover Components Against Earthquake

- Examples of crossover components between base-isolated and non-isolated building/equipment include piping, cable trays, air conditioner ducts and power cable conduit pipes and so on. All these components must maintain their integrity against displacement caused by earthquake.
- Methods that can be employed to cope with displacement include the strategic routing of piping and the use of expansion joints, etc. A choice is made by utility.

  Any method other than the above for coping with displacement can be allowed provided that its validity is demonstrated.

1) Considerations for Routing of Piping

- When calculating displacement, one should take the sum of absolute values of maximum displacement of base-isolated structure and non-isolated structure or the maximum values of time historical relative displacement on the both structures, as a general rule.

  This is because the base-isolated structure vibrates with long period and the coincidence of the peak displacement is more likely to occur at the base-isolated structure and the non-isolated structure.
- The calculation of seismic load can be done using the multiple input response spectrum analysis or the multiple input time history analysis.
- Since the crossover components suffer repeated large displacement in a short period of time, their integrity during earthquake shall be verified in consideration of failure modes such as “failure by fatigue” and “breakage by tension.”
- Seismic design methods of the crossover components are similar to the seismic design methods for non-isolated structures. Therefore, the methods prescribed by JEAC4601-2008 shall apply, as a general rule.

  JEAC4601-2008 prescribes the allowable stresses of piping including the mean stress for gross section due to axial force for purpose of “bringing attention to the need to give flexibility to piping between buildings that is prone to relative displacement during earthquake”. In consideration of the above, JEAC4601-2008 can be applied to the design of crossover piping installed in the seismic isolation structure.
- It is desirable that the validity of design methods for crossover piping, etc., used with seismic isolation structures is confirmed by verification and/or ultimate strength tests.

2) Considerations for the Use of Expansion Joints, etc.

- When expansion joints are to be used, the utility shall give attention to the service environment and choose products that have reliable capability against forced relative displacement during earthquake.
- Since expansion joints, in general, are designed to withstanding slow period displacement like thermal displacement, it shall be ensured that the expansion joints chosen for implementation withstand relatively short period displacement caused by earthquake. If expansion joints are pressurized, it shall be ensured that they can withstand both earthquake and internal pressure.
- The impact of aging or the maintainability of performance shall be evaluated.
- At least in the meantime, the reliability of expansion joints shall be verified by testing.[*1] Expansion joints are allowed to be put to actual use only within the range of capabilities confirmed by testing (in terms of the allowable displacement and the cumulative fatigue, etc.).[*2]

  *1: In the testing, it is necessary to address factors such as the inertial force from the non-isolated structure during earthquake, the service environment (temperature, internal pressure, the number of forced displacement during earthquake, fatigue, etc.) and the progress of aging.

*2: For high temperature and high pressurized piping (particularly in the case of BWR main steam piping which includes radioactive substance), the preferred method for coping with relative displacement would be strategic routing and the use of expansion joints is not recommended. Nevertheless, the use of expansion joints may be allowed if their applicability is verified by testing.

(Points Requiring Attention on Review)

(1) Impact on Seismic Isolation Functions

- Has the utility evaluated the potential impacts of crossover piping, crossover floor or the like on functions of the seismic isolation during earthquake?
- Since the evaluation is normally done by analysis, require the utility to submit the analysis result.
- If the utility has relied on testing for verification, require the utility to report the test method and the test result.
- Examples of points requiring attention:
  - -- Is not there something (e.g. doorway for the transportation of goods) that may obstruct the motion of the base-isolated structure during earthquake?
  - -- Is the clearance between the base-isolated structure and the non-isolated structure large enough and well maintained?
  - -- Is not the friction between the crossover floor and the base-isolated structure so large that it may restrict the motion of the base-isolated structure during earthquake?

(2) Maintaining the Integrity of Crossover Piping, etc., during Earthquake

- Examine how the failure modes of crossover piping, etc., have been identified, how displacement in response to earthquake have been evaluated and check the result of assessment of integrity.
- Examine the seismic load calculation method.
- If expansion joints are used, check the test result to ensure that it justifies the conditions under which they are going to be used. (For example, confirm that the maximum displacement during earthquake is smaller than the maximum absorbable displacement confirmed by testing.) Confirm that expansion joints are put to actual use only within the range of capability confirmed by testing.
- Check the fatigue assessment result and durability (aging) assessment result.

5.6 Load Combination and Allowable Limits

(1) Combination of Loads

Seismic load and other loads shall be appropriately combined according to provisions in the New Rules.

If there is any load that arises due to the implementation of a seismic isolation structure, it shall be considered as required when combining loads.

(2) Allowable Limit for Seismic Isolation Device

- The seismic isolation device shall be able to maintain its functions in the presence of a seismic load caused by the design basis ground motion that is appropriately defined corresponding to the classification of seismic importance.
- The allowable displacement limit of the seismic isolation device shall be determined by an appropriate method and the utility shall demonstrate the validity of the allowable displacement limit.
- The allowable displacement limit may be determined using either of the following methods:
  - (i) Determination from the ultimate displacement of the seismic isolation device or the crossover piping that connects between base-isolated building/equipment and non-isolated building/equipment.
  - (ii) Determination from the viewpoint of satisfying performance goals for core damage frequency and containment failure frequency based on the risk assessment. Specifically, the methodology of seismic PSA is can be used in the second method (ii).

(3) Allowable Limit for the Superstructure and the Substructure

- Superstructure

  With building isolation, the allowable limits for the building shall be defined to satisfy the criteria on the allowable stress prescribed by commonly accepted safety standards and guidelines, as a general rule.

  The allowable limits for facilities that are placed on a building structure shall be as prescribed by the New Rules.

  With equipment isolation, the allowable limits shall be as prescribed by the New Rules.
- Substructure

  The allowable limits for the substructure shall be as prescribed by the New Rules.

(Commentary)

(1) Combination of Loads

- In the designing of seismic isolation structures, the combination of loads is in a similar manner as it has been considered in the designing of non-isolated power reactor facilities.

The compliance with the New Rules is required.

- That is to say, the utility is expected to consider the combination of seismic load and other loads according to the ongoing practices (established for the designing of non-isolated power reactor facilities).
- If there is any load that arises specifically due to the implementation of seismic isolation (e.g. additional load at the time of replacement of seismic isolation devices), it shall be properly taken into account.

(2) Allowable Limit for Seismic Isolation Device

- Allowable limits for steel frame
  Reference shall be made to the allowable stress levels used in the design of conventional non-isolated structures at nuclear power facilities.
- Allowable limit for seismic isolation elements
  See Section 5.3 “Basic Performance Requirements for Seismic Isolation Device” for discussions on allowable limit for seismic isolation elements.
- Dampers and other seismic isolation elements with a moving mechanism need to have their allowable limit confirmed by testing. The dynamic properties of the base-isolated structure (response acceleration, velocity, displacement, etc.) shall be monitored while testing and the testing should cover full ranges of anticipated dynamic properties.
  Such testing may be omitted, however, if allowable limit can be determined by an alternative method.
- The implementation of the base-isolated structure may significantly affect the seismic safety of crossover piping, etc., because of increased displacement during earthquake. Therefore, when designing the seismic isolation device, it is necessary to determine the allowable displacement limit by an appropriate method and to demonstrate the validity of the allowable displacement limit.
- The allowable displacement limit of the seismic isolation device may be determined using either of the following methods:
  (i) Determination from the ultimate displacement of the seismic isolation device or the crossover piping that connects between base-isolated building/equipment and non-isolated building/equipment.
  When calculating the allowable displacement limit of the seismic isolation device, the deterministic approach of conventional seismic design practices can be used. Specifically, allowable displacement limit can be determined in consideration of the followings:
  -- Ultimate displacement of the seismic isolation device
  -- Clearance between the base-isolated structure and non-isolated structures
  -- Ultimate displacement of crossover piping, etc.
  -- Variation in response
  -- Any other factor that may restrict displacement

(ii) Determination from the viewpoint of satisfying performance goals for core damage frequency and containment failure frequency based on the risk assessment.

When the seismic isolation structure is applied, it is possible to assume that seismically vulnerable points are limited to a certain components unique to the seismic isolation structure such as crossover piping. In that case, a probabilistic method can be applied for the determination of the allowable displacement limit. Specifically, the allowable displacement limit can be determined with a view to satisfying performance goals for the core damage frequency and containment failure frequency utilizing plant risk assessment. Seismic PSA is one of effective methods.

(3) Allowable Limit for Superstructure and Substructure

- Building isolation

  Since seismic isolation structures have a relatively long natural period, the superstructure is subjected to semi-static load. If the superstructure gets into plastic state during earthquake, it is possible that the plastic deformation of the superstructure would significantly increase. Considering that, it shall be ensured that the allowable limit for the building satisfy the criteria on the allowable stresses established by commonly accepted safety standards and guidelines, as a general rule.

  In the case of building isolation, the allowable limit for facilities that are placed in the building shall be as prescribed by the New Rules.
- Equipment isolation

  The allowable limits for facilities shall be as prescribed by the New Rules.
- The allowable limit for the substructure shall be as prescribed by the New Rules, according to conventional design practices.

(Points Requiring Attention on Review)

(1) Combination of Loads

- Has the utility properly considered the combination of seismic load and other loads? What are the other loads combined?

  Confirm the coverage of all load combinations that are addressed by conventional seismic design practices.
- Is there any load that arises specifically due to the implementation of a seismic isolation structure?

(2) Allowable Limit for Seismic Isolation Device

- Confirm what standards and guidelines allowable limit (the allowable stress, the allowable strain, etc.) of seismic isolation device are based on.
- Confirm how the utilities determined the allowable functional limit. Require the utility to submit the materials (test results, etc.) on which the allowable functional limit were based, and confirm the validity of them.

- Review the allowable displacement limit of the seismic isolation device and verify the method of its determination.

(3) Allowable Limit for Superstructure and Substructure

- Building isolation
  Is the building's response generally within the allowable stress?
  Does the response of components placed in the building satisfy the conditions for the maintainability of performance?
- Equipment isolation
  Does the response of components satisfy the conditions for the maintainability of performance?
- Do the allowable limits for the substructure comply with the New Rules?

6. Review on Risk Assessment Stage

6.1 Approaches to Risk Assessment for Base-Isolated Structure

- When implementing the base-isolated structure, the presence of “residual risks” shall be acknowledged and efforts shall be made to make it as small as practicable.

(Commentary)

- A commentary in the Regulatory Guide for Reviewing Seismic Design describes as follows:

  From a seismological standpoint, the possibility of stronger earthquake ground motions which may exceed the one formulated as above (1) (Formulation of earthquake ground motions for seismic design) exists. That is, in formulating the seismic design earthquake ground motions, the “Residual Risks” exist, which may cause serious damages to the Facilities by the ground motion exceeding the formulated design basis ground motions, or massive radioactive release from the Facilities, or cause as a consequence radiological exposure hazards to the public in the vicinity of the Facilities.

  Therefore, every effort should be made, at the design of the Facilities (in the basic design stage and subsequent stages), to minimize the “residual risks” to the extent “as low as practically possible” by appropriate attention to the possibility of ground motions exceeding the formulated design basis.
- Therefore, when implementing the base-isolated structure, like when constructing the non-isolated structure, efforts shall be made to minimize “the residual risks.”
- There is no example of the actual risk evaluation of nuclear power facilities. In the future, practical application of risk evaluation including policies and contents should be enriched by accumulating lessons learned from the evaluation results of utilities and reviews.

6.2 Methodology of Risk Assessment for Base-Isolated Structure

- The residual risks can be evaluated by probabilistic safety assessment methods, specifically, the methodology of seismic PSA.
- A methodology other than that of seismic PSA may be used, provided that its validity is demonstrated.

(Commentary)

- The Nuclear Safety Commission (NSC) made the statement in a document titled "About the Revision, etc., of Regulatory Guides on Seismic Safety Such as the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities" on September 19th in 2006.
- The Nuclear Regulation Authority (NRA) explained "Relationship between amount of radioactive material release and occurrence frequency" on April 3rd in 2013, and following this, made the statement "Main issues related to the safety goal discussed until last NRA meeting (April 3, 2013)" on April 10th in 2013.

○ NSC's statements on the residual risks (September 19, 2006)

Excerpt from "About the Revision, etc., of Regulatory Guides on Seismic Safety Such as the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities" (NSC)

The Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities does not have any provision that demands the submission, at the time of application for reactor establishment license, of a report on the quantitative assessment of "the residual risks" (The risks which may cause serious damages to the facilities by the ground motion exceeding the formulated design basis ground motions, or massive radioactive release from the facilities, or cause as a consequence radiological exposure hazards to the public in the vicinity of the facilities.) NSC, however, believes in the significance of conducting a quantitative assessment of "the residual risks" from the viewpoint of paving the way to full employment of probabilistic safety assessment in safety regulatory activities in the future, and therefore, it is important to request the concerned reactor licensees to conduct a quantitative assessment of "the residual risks" under the supervision of the regulatory body, as something apart from safety reviews.

When conducting such assessment, utilities are encouraged to make good use of advanced assessment methods based on the latest knowledge such as the method of probabilistic safety analysis (PSA).

○ NRA's statements on the safety goal (April 3, 2013)

Excerpt from "Main issues related to the safety goal discussed until last NRA meeting (April 3, 2013)" (NRA)

(i) Special Committee on Safety Goal under the NSC particularly investigated the safety goal until 2006(*), and this result would be a solid base to discuss the safety goal for the NRA.

＊ *Interim report of investigation and review on the safety goal (December, 2003) / About performance goal of power-generation LWR reactor – the performance goal corresponding to the draft safety goal - (March 28, 2006)*

(ii) However, taking into account environment contamination by radioactive materials considering the Fukushima Dai-ichi NPPs accident, the influence on environment due to unexpected nuclear accident should be as low as possible. Specifically, in reference to examples of other countries, following requirement for power-generation reactors should be added;

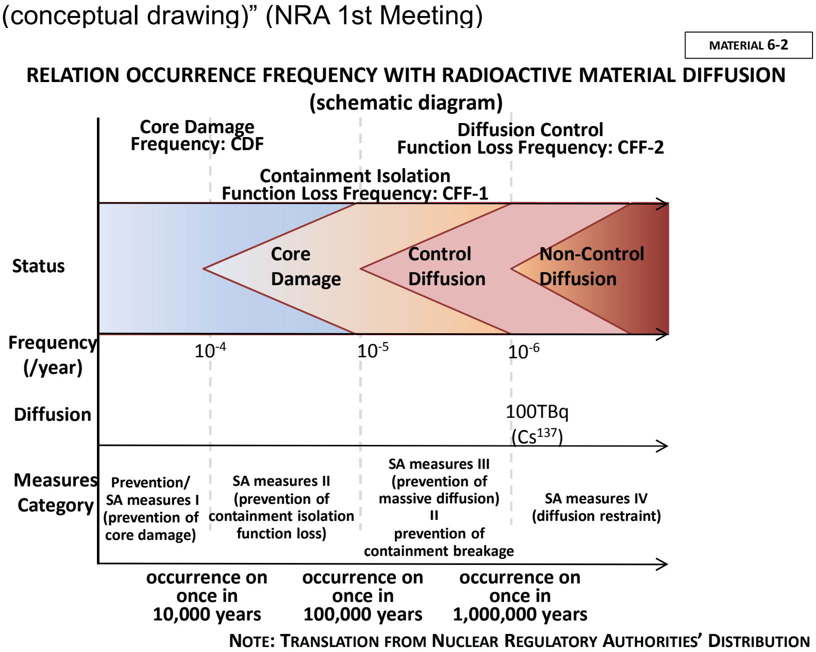
- The occurrence of accident resulting in Cs-137 release of 100TBq or larger should be less than the probability of approximately 10^{-6} per year.

(iii) In consideration of the purpose of introducing back-fitting system to the regulation, The safety goal shall be applied to all of power-generation reactors.

(iv) The safety goal is a goal which the NRA aims to achieve in process of carrying out NRA's regulation activities.

(v) The NRA, which seeks consecutive improvement of nuclear safety, continues the argument about the safety goal and other remaining issues offered to the NRA on March 6th in 2013.

Excerpt from "Relationship between amount of radioactive material release and occurrence frequency (conceptual drawing)" (NRA 1st Meeting)



- Considering the activities of the NRA, the Guidelines accept probabilistic safety assessment (seismic PSA) as a method that can be used for the assessment of the residual risks.
- When implementing seismic PSA, utilities may seek compliance with “Standard for Procedure of Seismic Probabilistic Safety Assessment for Nuclear Power Plants” (Atomic Energy Society of Japan), which prescribes fragility evaluation methods for building isolation and equipment isolation.

  During fragility analysis, it is important to clarify the analysis conditions particularly for those components which will have a larger probability of fracture due to the implementation of the seismic isolation structure (e.g. crossover piping, etc.).
- It is allowed to use a methodology other than that of probabilistic safety assessment if the validity of the chosen method is demonstrated.

7. Review on Construction Stage

7.1 Quality Control for Seismic Isolation Elements

- For assurance of the quality of seismic isolation elements throughout the in-service period, the procurement, production, inspection, installation of seismic isolation elements, checking clearance gap from adjacent structure, performance testing of seismic isolation elements including displacement gauging device, etc., shall be done with an appropriate quality assurance program equivalent to the one applicable to the superstructure.

(Commentary)

- Quality control activities at nuclear power plants are conducted with appropriate quality control programs for all stages from the design stage to the operation stage.
- Since any failure of seismic isolation elements may directly lead to the failure of superstructure, the level of quality control for seismic isolation elements shall be equal to that for the superstructure and substructure.
- For quality control of seismic isolation elements, it is important to be able to understand the characteristics of seismic isolation elements under actual service conditions during the in-service period. Therefore, the quality control of seismic isolation elements shall mainly rely on characteristic testing and product inspection, and the inspection shall cover all products, as a general rule.
- In the case where the product inspections are limited, it shall be combined with characteristic test result, etc., to make the quality control more comprehensive.
- In Paragraph (6) “Seismic Isolation Element Characteristics for Seismic Response Analysis” of Section 5.4, it has been stated: “Upon the completion of seismic isolation elements for actual implementation, the characteristics such as stiffness and damping factor shall be evaluated by testing all products, as a general rule, in order to confirm the validity of the seismic isolation element characteristics used in seismic response analysis.” As prescribed, the characteristics of seismic isolation elements confirmed by the inspection mentioned above should be used for verifying the characteristics used for the seismic response analysis.
- It is necessary to check the clearance gap between seismic isolation device and adjacent structure, installation and availability of displacement gauging device and implementation of performance testing of seismic isolation device.

7.2 Pre-service Inspection of Base-Isolated Structure

- Before starting operation of the power plant, the utility shall inspect the base-isolated structure to confirm the availability of required functions.
- The inspection data must be recorded.

(Commentary)

- During the pre-service inspection, the utility shall visually inspect the seismic isolation devices, take measurements and keep records to confirm the seismic isolation device has been properly constructed.
  In addition, the utility shall inspect the base-isolated structure for its capability of motion during earthquake (e.g. ensuring the absence of obstacle such as inappropriate implementation of crossover components which disturb the motion of the base-isolated structure) by both visual inspection and testing (static load testing, for example). However, it is not meant to require the testing if conducting test is evidently difficult.
- The utility shall plan periodical inspection programs clarifying the items to be addressed in the inspections and record initial inspection data. Those data would be compared with data measured in the in-service inspections.
- See “Maintenance Standard for Seismically Isolated Buildings” (2007) from the Japan Society of Seismic Isolation (JSSI) for information about the method of pre-service inspection of seismic isolated buildings and about the values to be inspected. No maintenance standards have been prepared for the equipment isolation; the above standards for the building isolation may be referred to in the meantime as the source of some useful information.
- Table 7.2-1 shows an example of the scope of pre-service inspection.

(Points Requiring Attention on Review)

- Has the seismic isolation device been properly constructed? (e.g., is the vertical deformation of seismic isolation element within the allowable design range?)
- Does the seismic isolation structure have a sufficient freedom of movement during earthquake? Isn’t there any obstacle to its motion?
- Has the utility collected the initial data that should serve as the baseline for periodical in-service inspection?

Table 7.2-1 Scope of pre-service inspection (example)

	Timing	Scope (example)
Pre-service inspection	Appropriate timing before completion of construction	(i) Inspection targets Seismic isolation elements, fire protection cover, the seismic isolation story and its periphery, piping, cables and flexible sections of them, dustproof cover, etc. (ii) Inspection methods Visual inspection and measurement (*) Static force testing, etc. (iii) Target components/locations Visual inspection: all Measurement: all (iv) Inspection procedure - Visual inspection: Check for scar, rust, dust adhesion, corrosion, oil leakage, interference, etc. - Measurement: Measure the horizontal/vertical displacements and dimensions of seismic isolation elements, the degree of uneven settlement, etc. - Testing: Static load testing (to test the performance of the base-isolated structure as a whole) -- Evaluate the stiffness, etc., of the base-isolated structure as a whole. -- Confirm the freedom of movement during earthquake. (Check for any obstacle to the movement and for the possibility of interference with nearby equipment, for example.) The purpose of the pre-service inspection is not only the confirmation of proper construction but also the collection of initial values that should serve as the baseline for in-service inspections. (v) Control target values Control target values are defined by the utility. For guidance on the definition of control target values, see “Maintenance Standards for Seismically Isolated Buildings” (2007) from JSSI.

∗: Measure the rubber bearing displacement, major dimensions on dampers, damper displacement, etc.

If 100% inspection is deemed unnecessary because the variation of seismic isolation element characteristics among products is evidently so small that it cannot affect the result of analysis of seismic response of seismic isolation structure, it may be substituted by sampling inspection provided that its validity is demonstrated.

7.3 Performance Confirmation of Seismic Isolation Structure

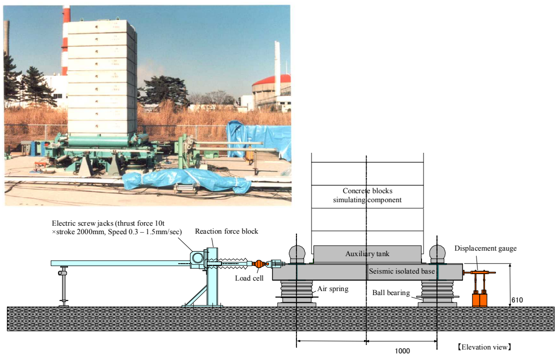
- Vibration characteristics of the seismic isolation structure such as natural frequency, damping ratio shall be evaluated by performance confirmation testing, etc.
- Testing results related to property of seismic isolation shall be recorded.

(Commentary)

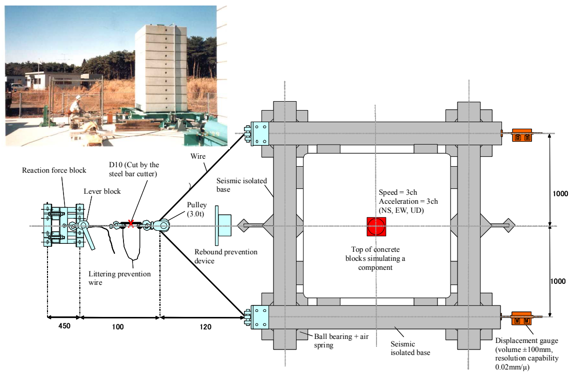
- In order to confirm whether the seismic isolation function performs as designed, vibration characteristics of the seismic isolation structure such as natural frequency, damping ratio in the direction of horizontal and vertical shall be evaluated by static load testing, free vibration resting and so on.
- Examples of the performance confirmation methods are described in chapter IV, iii, 2 “Three-Dimensional Equipment Isolation System”.
- In the case of performance confirmation, it is necessary to give attention to the rocking motion because the rocking motion would induce vertical response.

Table 7.3-1 List of characteristics testing

	Characteristics	Testing result	Design value	Remarks
Horizontal				
Vertical				



[Static Load Testing]



[Free Vibration Testing]

Fig. 7.1-3 Static load testing and free vibration testing in horizontal direction

8. Review on Operation Stage

8.1 In-service Inspections

- The seismic isolation device shall maintain the required functions throughout the in-service period. To ensure that, it is necessary to inspect the base-isolated structure periodically. - In a situation where product tests with specimen which is separately kept under the environment condition same with actual device or static load test, those tests should be conducted.

(Commentary)

- The utility shall plan in-service inspection programs in order to inspect base-isolated structure periodically. The utility may refer to "Maintenance Standard for Seismically Isolated Buildings" (2007) from JSSI for information about maintenance methods and control values for the building isolation. No maintenance standards have been prepared for the equipment isolation; the above standards may be referred to in the meantime as the source of some useful information.
- Visual inspection and measurement shall be the methods used in the in-service inspections.
- In a situation where product tests with specimen which is separately kept under the environment condition same with actual device or static load test, those tests should be conducted.
- If inspection reveals a change in the performance of seismic isolation elements due to causes such as aging, the utility shall verify, by means of seismic response analysis, for example, that the seismic isolation device still maintains the required functions.
- When the specifications of the superstructure greatly change from the situation in the design stage (e.g. change of mass due to the replacement of equipment in the case of equipment isolation), the utility shall evaluate the impact of the change.

Table 8.1-1 gives an example of the frequency and scope of periodical inspections.

(Points Requiring Attention on Review)

(1) Examining the in-service inspection program

Is the in-service inspection program adequate (in terms of scope and frequency)?

(2) Points of the in-service inspections

- By visual inspection and measurement, the utility shall check for scar, rust, dust adhesion, oil leakage and deformation.
- If performance is verified by testing, gain information about the test method.
- The utility should compare the test result with the pre-service inspection result (initial values) to be able to detect any change in the performance.
- If the inspection result suggests a change in performance, require the utility to evaluate its impact on the capability of the superstructure by analysis, etc.

- If a change such as the replacement of equipment may affect the effectiveness of seismic isolation, require the utility to evaluate the impact by analysis, etc.

Table 8.1-1 Frequency and scope of in-service inspections (example)

	Frequency (example)	Scope (example)
In-service inspections	Annual inspection (*1)	(i) Inspection targets Seismic isolation elements, fire protection cover, the seismic isolation story and its periphery, piping, cables and flexible sections of them, dustproof cover, etc. (ii) Inspection methods Visual inspection (iii) Inspection procedure Check for scar, rust, dust adhesion, corrosion, oil leakage, interference, etc. (iv) Target components/locations All members (v) Control target values Control target values are defined by the utility. Control target values shall be appropriately set so that property change of the seismic isolation elements will not impair the required functions of the seismic isolation device.
	- At 5 and 10 years after construction completion - After every 10 years in the subsequent period	(i) Inspection targets Seismic isolation elements, fire protection cover, the seismic isolation story and its periphery, piping, cables and flexible sections of them, etc. (ii) Inspection methods Visual inspection and measurement Testing with specimens kept in an environment same with the service environment of actual products, or static load testing, etc. (iii) Inspection procedure - Visual inspection: Check for scar, rust, dust adhesion, corrosion, oil leakage, etc. - Measurement: Measure the horizontal/vertical displacement and dimensions of seismic isolation device, the degree of uneven settlement, etc. - Testing: Testing with specimens kept in an environment same with the service environment of actual products: Evaluate the stiffness and damping ratio. Static load testing (performance of the seismic isolation structure): Confirm the freedom of motion during earthquake. (Check for any obstacle to the movement and for the possibility of interference with nearby equipment, for example.) (iv) Target components/locations - Visual inspection: all - Measurement: by sampling (v) Control target values Control target values are defined by the utility. For guidance on the definition of control target values, see “Maintenance Standard for Seismically Isolated Buildings” (2007) from JSSI. (vi) Remarks Verify that the seismic isolation device maintains the required function of seismic response reduction by seismic response analysis, etc.

*1: It is assumed that inspection is performed at the time of annual inspection of the plant.

8.2 Performance Verification during/after Earthquake

When earthquake occurs, the response of the base-isolated structure shall be monitored by an appropriate method. Depending on the magnitude of seismic response, the integrity of the superstructure, substructure and seismic isolation device shall be checked for the detection of any damage, the current position of the base-isolated structure shall be determined, and the performance shall be verified that the base-isolated structure maintains required functions.

(Commentary)

- To enable the monitoring of the seismic response of the base-isolated structure during earthquake, the utility must install accelerometers and displacement gages to appropriate positions.
- The behavior of the base-isolated structure during earthquake is confirmed by the magnitude of relative displacement between the superstructure and substructure, by the response acceleration measured immediately above the seismic isolation story, or in terms of the both.

  The utility shall monitor the orbits and seismic response acceleration of the base-isolated structure during earthquake.

  Even though compromise may be allowed if the installation of above-mentioned instruments is difficult due to restrictions imposed by the size of the base-isolated structure, the utility shall make the best effort to enable the measurement of orbit.
- The performance verification of the base-isolated structure shall involve the confirmation of structural integrity and required functions.

  -- Confirmation of structural integrity

  The utility shall confirm the structural integrity of the base-isolated structure and crossover components by inspection, etc.

  The inspection methods should be basically visual inspection, measurement, etc. The verification may be complemented by analysis as required.

  -- Confirmation of required functions

  For continuing use of seismic isolation device after earthquake, the utility shall confirm that the devices can appropriately function against the next earthquake in the future by test, analysis, etc.

  It is necessary to determine whether or not the seismic isolation devices worked during the earthquake. If it did, the utility shall demonstrate that the devices can appropriately function against the next earthquake in the future.

  In the case of steel rod dampers that may undergo a change of characteristics after an earthquake, the utility shall carefully evaluate the acceptability of their continuing use.

  If there is residual displacement on the seismic isolation device, the structural integrity of crossover components shall be inspected. The utility shall make a judgment on the acceptability of their continuing use and take measures as required.

- Other remarks:

  It is necessary to inspect the seismic isolation device with extreme attention when it encounters an earthquake large enough to work for the first time after the construction.

  The utility shall inspect the seismic isolation device, watching out for phenomena such as the loosening of bolt, and also to the increase of plasticity which depends on the characteristics of seismic isolation device.

  After earthquake, the utility shall confirm the absence of obstacles to the functioning of the seismic isolation device during earthquake such as the placement of some equipment within the range of motion of the base-isolated structure.

- After a large ground motion that might have caused the seismic response beyond linear limit of the seismic isolation elements, the utility shall consider removing the seismic elements for the testing of their performance.

(Points Requiring Attention on Review)

- Find out the types of seismic response of base-isolated structure that are monitored, as well as the monitoring method and the positions at which instruments are installed.
- The utility should compare the inspection result with the pre-service inspection result in order to detect any change in the performance.
- Did the seismic isolation devices work during earthquake? If it did, require the utility to submit earthquake observation data or orbit, for example, to be able to examine the position of the superstructure after the earthquake.

  If the superstructure has not gone back to the initial position, the utility shall move it back to the initial position or demonstrate that residual displacement of the seismic isolation device would not affect required function of the device by analysis.

  Inspect crossover components to be able to detect any residual displacement.
- Require the utility to conduct analytic evaluation of capability of the seismic isolation device to reduce seismic response if necessary.

  If the utility has decided to continue using it without replacement, even though the earthquake has caused a change to the characteristics of seismic isolation device, require the utility to confirm that the function of reducing seismic response can be maintained.

9. Documentation Management of Design Data, Monitoring Data, etc.

- With each implementation of the seismic isolation structure, the utility shall keep records of design data, etc.
- The utility shall keep monitoring data of the base-isolated structure recorded during earthquake.

(Commentary)

Considering the lack of data based on the past experience of implementing the seismic isolation structure at NPPs, utilities are requested for the time being to contribute to the accumulation of design experience and knowledge through the keeping design data, analysis result, etc.

- Documentation policy
  - -- Experts not involving the concerned design can understand the overview and easily review the design and assessment results for the verification of their validity.
  - -- Compliance of the implemented base-isolated structure with the Review Guidelines shall be demonstrated.
- Topics to be addressed

  Data shall be collected throughout the plant life cycle:
  - -- Design stage
    - --- Overview of seismic isolation device

      (overall structural drawing, characteristics, specifications and layout of the seismic isolation device, overview of the base-isolated structure, etc.)
    - --- Classification of seismic importance of seismic isolation device
    - --- Design basis ground motion
    - --- Allowable stress
    - --- Structural specifications

      The use of recorded specifications (pertaining to the seismic isolation device layout, stiffness, restoring force characteristics, damping coefficient of dampers, frictions, frame structure specifications, weight of seismic isolation structure, etc.) shall enable the follow-up of results of natural frequency analysis and seismic response analysis.
    - --- Result of natural frequency analysis
    - --- Result of seismic response analysis on the base-isolated structure
    - --- Relative displacement between base-isolated and non-isolated structures
    - --- Method and evaluation result performed on the integrity of seismic isolation device during earthquake
    - --- Evaluation result on the validity of analysis model and related test results
    - --- Seismic evaluation results (on structural integrity and the maintainability of required functions)

- Risk assessment stage

  (Seismic response)

  Assessment targets

  Failure modes and vulnerable area/part of components/elements

  Indices for failure/damage evaluation (stress, etc.):

  Median and deviation of response to each ground motion level and the evidence of the estimation

  Median and deviation of the response factor and the evidence of the estimation

  (Seismic capacity)

  Median and deviation of the seismic capacity and the evidence of the estimation

  (Analysis result)

  Core damage frequency

  Fussell-Vesely (FV) Importance, etc.

  (Construction stage)

  Pre-service inspection result

  Quality assurance program

  (Operation stage)

  In-service inspection result

  Monitoring data of the base-isolated structure recorded during earthquake

  Inspection results required for continuing use after earthquake

  Exposure testing results of seismic isolation device/element

- Other types of information as required

Ⅲ. Conclusion

Conclusion

The Japan Nuclear Energy Safety Organization (JNES) established The Seismic Isolation Standard Subcommittee in 2009 under The Seismic SSCs Standard Committee, which were formed by experts from the outside, and started to prepare guidelines for the seismic isolation systems. This subcommittee was composed of two working groups (WGs): the Building Isolation Working Group and the Equipment Isolation Working Group. In the two working groups, the guidelines were discussed, focusing on either building isolation or equipment isolation and giving attention to the topics listed below. This document, the Technical Review Guidelines for Structures with Seismic Isolation, was compiled based on the results of these discussions.

Topics:

- Trends concerning seismic isolation in Japan and abroad
- Scope
- Definitions of technical terms
- Basic policy
- Review points on the seismic design stage
- Review points on the risk assessment stage
- Review points on the construction stage
- Review points on the operation stage
- Preparation and preservation of design data, etc.

With the following features, the Technical Review Guidelines for Structures with Seismic Isolation will be found useful not only in Japan but also in other countries of the world:

- Approach to the reviewing of seismic isolation systems at different points in the plant lifecycle from the design stage to the operation stage.
- Different roles that a seismic isolated structural design may play in geographical regions of high, moderate and low seismicity.

In order to help the understanding of technical descriptions in the guidelines and also some important points about the reviewing process, this document contains supplementary materials such as examples of design and assessment of seismic isolation systems.

IV. Supplement (Examples of Seismic Isolation Trial Design and Preliminary Assessment)

i. Introduction

The seismic isolation technology, including both building isolation and equipment isolation as two major categories, is already regarded as matured technology thanks to the valuable research and implementation history of more than 20 years in both nuclear and non-nuclear fields.

At the time of the Niigata-ken Chuetsu-oki Earthquake of July 2007, the ground motion at the Kashiwazaki Kariwa Nuclear Power Plant was 2.5 times greater than the design basis level. In response to the earthquake took place, Unit 2 at the power plant that was being started up, and Units 3, 4 and 7 that had been operation, were shut down automatically, and Unites 1, 5 and 6 were in scheduled outage. The plant maintained the capabilities for shutdown, cooling and containment without producing any safety concern. However, about 3,700 cases of troubles happened to plant facilities of low seismic classification. The troubles included the immobility of the door to the emergency response room, which prevented the smooth execution of emergency response activities. Learning from such experience, the utility pursued progress in the introduction of seismic isolated structural design to emergency administration buildings in order to ensure the smooth execution of emergency response activities. The utility has built seismic isolated buildings dedicated to such purposes at the Kashiwazaki Kariwa NPP, Fukushima Dai-ichi NPP and Fukushima Dai-ni NPP, for example.

The Earthquake Off the Pacific Coast of Tohoku of March 11, 2011 brought large tsunamis to the Fukushima Dai-ichi NPP, causing damages that led to the loss of reactor cooling capability and the release of radioactive materials from the containment vessels to the external environment. At both Fukushima Dai-ichi and Dai-ni NPPs, emergency response activities were led by the emergency response headquarters established inside the seismic isolated building that had been built by the utility, as mentioned above, learning from the experience of Niigata-ken Chuetsu-oki Earthquake. These seismic isolated buildings effectively protected the staffs from the threat of many aftershocks.

Given such background, the use of seismic isolation technology at nuclear power plants is believed to be the most effective way to increase the seismic safety margin at NPPs (both new and existing reactor facilities) and to achieve the further improvement of seismic resistance and plant reliability. Therefore, the use of seismic isolation technology at nuclear facilities is expected to become more common in the future. The study of seismic isolation technology for advanced reactors, etc., has already began.

In overseas, the Cruas NPP of France became, in 1985, the first nuclear power plant of the world having a seismic isolated building. A seismic isolated building was completed also at the Koeberg NPP in the Republic of South Africa.

The following is a list of examples provided herein concerning the design and assessment of seismic isolation applied structures at nuclear facilities:

Seismic isolated structure design examples:

- Example of seismic isolation reactor building design for PWR
- Example of common foundation type seismic isolation building design for BWR

- Examples of seismic isolated building design for advanced reactors
- Seismic verification testing of a computer system placed on a seismic isolated floor
- Three-dimensional seismic Isolation of floor
- Connecting piping designed to absorb relative displacement

Seismic isolated structure assessment example:

- Assessment of the failure probability of equipment isolation at reactor facilities

The example design of seismic isolation building for PWR and BWR are the designs developed by the electric power companies of Japan in a joint project as seismic isolation building designs for use at existing reactor facilities. The design examples of seismic isolation building for advanced reactors are from a joint development program conducted with the participation of electric power companies, plant manufactures and other stakeholders. Included herein are the articles concerning the development program and the testing of seismic isolation device, for example, that they have presented at a general meeting of the Architectural Institute of Japan (AIJ) and have been included in the Compilation of Academic Papers published by the AIJ.

As an example of equipment isolation, a section titled “Seismic Verification Testing of a Computer System Placed on a Seismic Isolated Floor” describes a seismic test performed by the Nuclear Power Engineering Corporation (NUPEC) at the Nuclear Power Engineering Test Center in Tadotsu. Included herein is an article from “The Current Status of Verification Test Projects for the Nuclear Power Facilities” (1993).

As a design example of crossover piping between seismic isolated and non-isolated buildings, which is identified as a challenge in the design of seismic isolation structures, “Connecting Piping Designed to Absorb Relative Building-to-Building Displacement” contains some materials presented by an electric power company in the First Kashiwazaki International Symposium on Seismic Safety of Nuclear Installations.

A section titled “Assessment of the Failure Probability of Equipment Isolation at Reactor Facilities” contains an article, concerning the methodology for the detailed assessment of the failure probability of entire seismic isolation system and the attempt to reduce the failure probability of emergency diesel generator by the use of seismic isolation, presented by JNES, the Japan Atomic Energy Agency, etc., at the Sixth National Symposium on the Safety and Reliability of Structures organized by the Japan Society of Civil Engineers.

These design and assessment examples support the examination of seismic isolation structures by supplementing “commentary” and “points requiring attention on review” of the Review Guidelines.

ii. Trial Design Examples of Seismic Isolation Structure

1. Design Examples of Building Isolation

1.1 Seismic Isolated Reactor Building for PWR

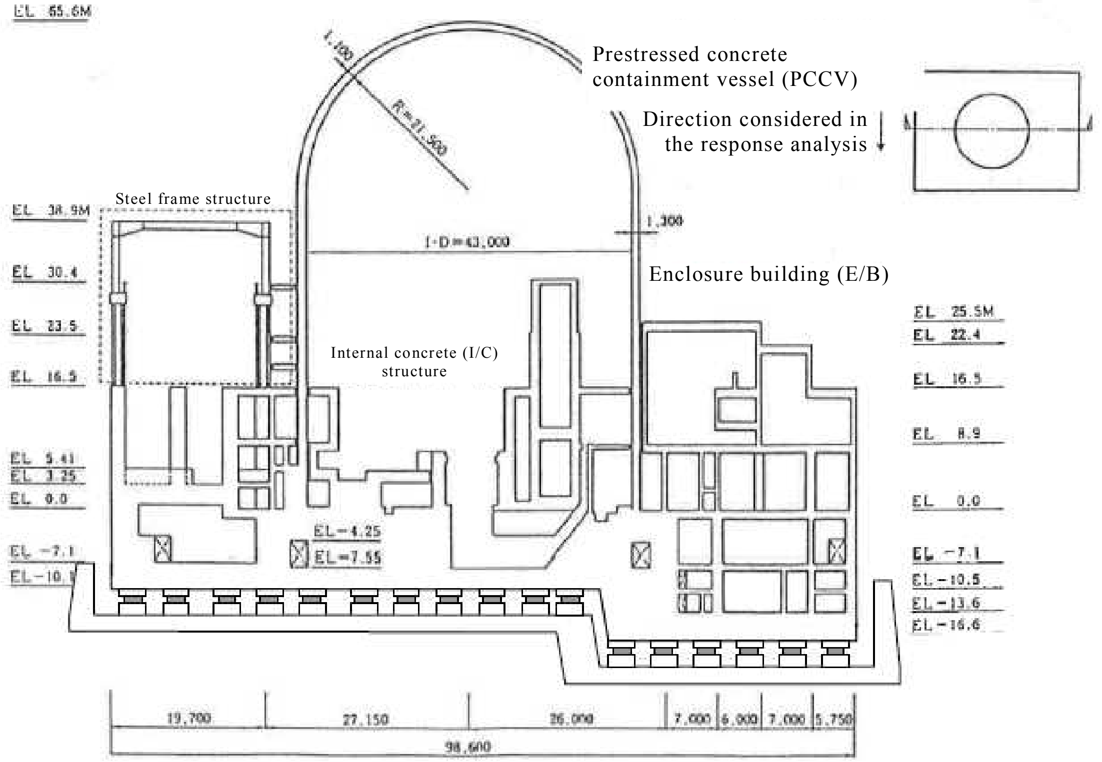
1.1.1 Introduction

The reactor building is a rigid structure mainly consisted of box frame type reinforced concrete. Therefore, the implementation of seismic isolated structural design to the reactor building is expected to ensure significant isolation effect because of a large difference between the natural period specific to the seismic isolation device and that of building structures, contributing greatly to the improvement of seismic safety. This section gives an example of seismic isolated building for the reactor building at a pressurized water reactor (PWR) plant (hereinafter, “PWR seismic isolated building”). In this example, the superstructure of the reactor building is of typical aseismic design, not the one rationalized by seismic isolation design. In this trial design example, the seismic isolation devices were designed and response results of those devices were confirmed to meet criteria by seismic response analysis.

1.1.2 Overview of the building

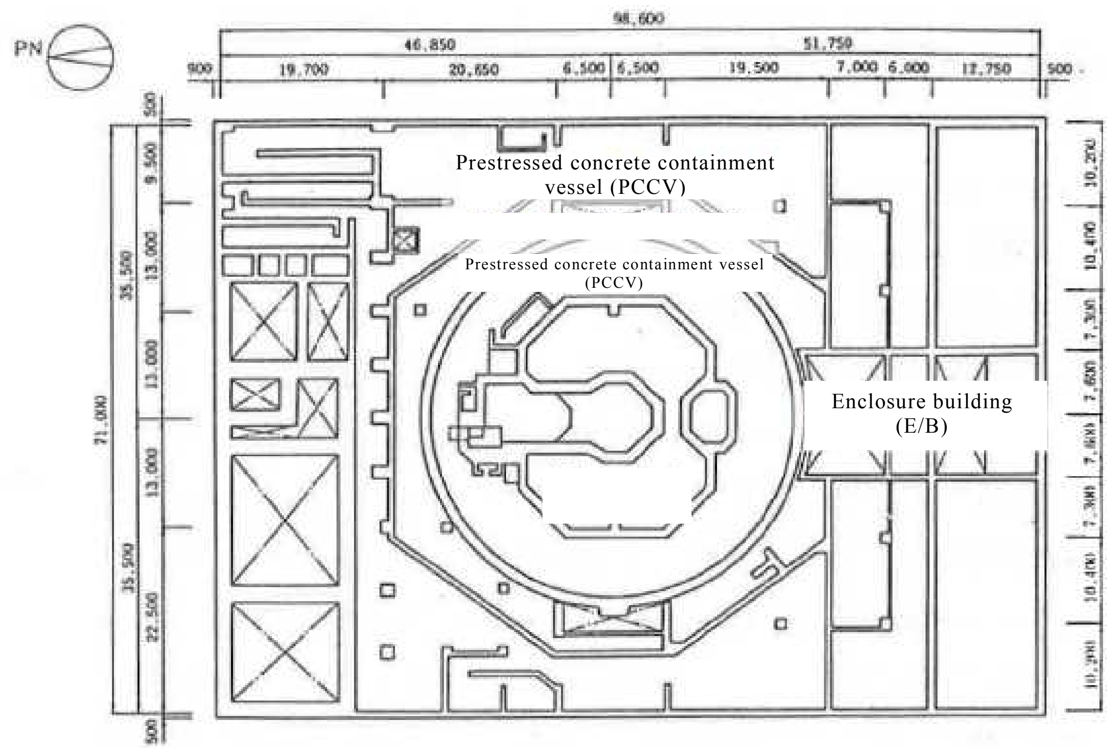
In this example, the PWR reactor building is a reinforced concrete structure (with the partial use of prestressed concrete and steel frame structure) having the basemat of approximately 100m x 72m and the height of about 76m (from the top surface of the superstructure to the top of building), and the weight of the isolated building structure is 3,225,000kN. Upon the rectangular foundation, there stand the prestressed concrete containment vessel (PCCV), the internal concrete (I/C) structure and the enclosure building (E/B). Lead rubber bearing (Shear modulus of elasticity of rubber is 0.392N/mm^2 at 15 degree C) is used as the seismic isolation device.

Fig. 1-1 and 1-2 show rough sectional and planar views of the reactor building. Table 1-1 lists the specifications of lead rubber bearing and its allowable strain/displacement limit and fracture limit. Figs. 1-3 and 1-4 show the design and layout of lead-plugged laminated rubber.



Sectional view

Fig. 1-1 Rough sectional view of reactor building (showing approximate position of the seismic isolated layer)



Planer view of the reactor building (at the elevation of 16.5m)

Fig. 1-2 Rough planar view of reactor building

Table 1-1 Specifications of lead rubber bearing

	Specifications		Rubber type: G4
Dimensions	Outside diameter (D)	(mm)	1600
	Lead plug diameter (Dp)	(mm)	424
	Rubber thickness per layer (tr)	(mm)	10
	Number of rubber layers (n)		24
	Total rubber height (Hr)	(mm)	240
	Steel plate thickness per layer	(mm)	5.8
	Number of steel plate layers		23
	Total thickness including rubber and steel plate thickness (Hp)	(mm)	373.4
	Primary shape coefficient S1 = D/4tr		40.0
	Secondary shape coefficient S2 = D/Hr		6.7
	Rubber plug height/diameter ratio (Hp/Dp)		0.88
Linear limit in the horizontal direction	Linear strain limit		2.5
	Linear displacement limit	(mm)	600
	Linear displacement limit / 1.5	(mm)	400
Bearing load and required number of lead rubber bearing s	Bearing load (P)	(kN)	9807
	Weight of the superstructure(W)	(MN)	3227
	Number of lead rubber bearings		329
	Long-term axial pressure	(N/mm^2)	5.25
Vibration characteristics	Horizontal period at the secondary stiffness Kh	(sec)	3.41
	Natural frequency in the vertical direction	Hz）	16.24
	Yield seismic intensity		0.130

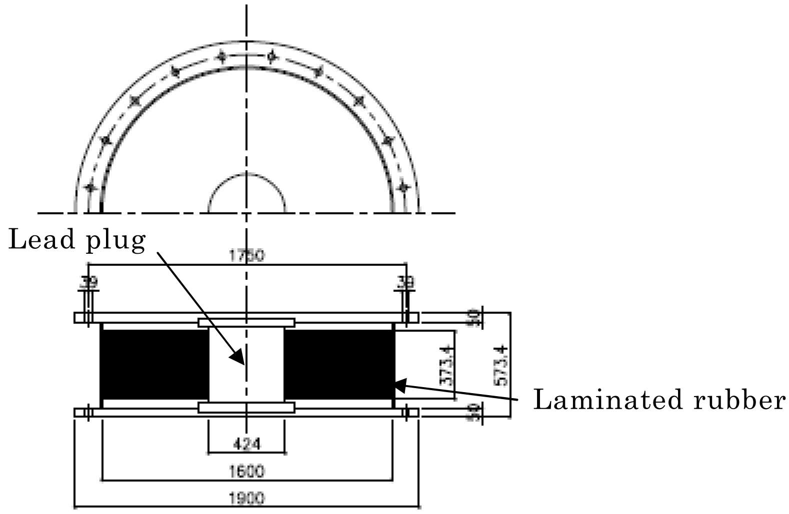


Fig. 1-3 Design of lead rubber bearing

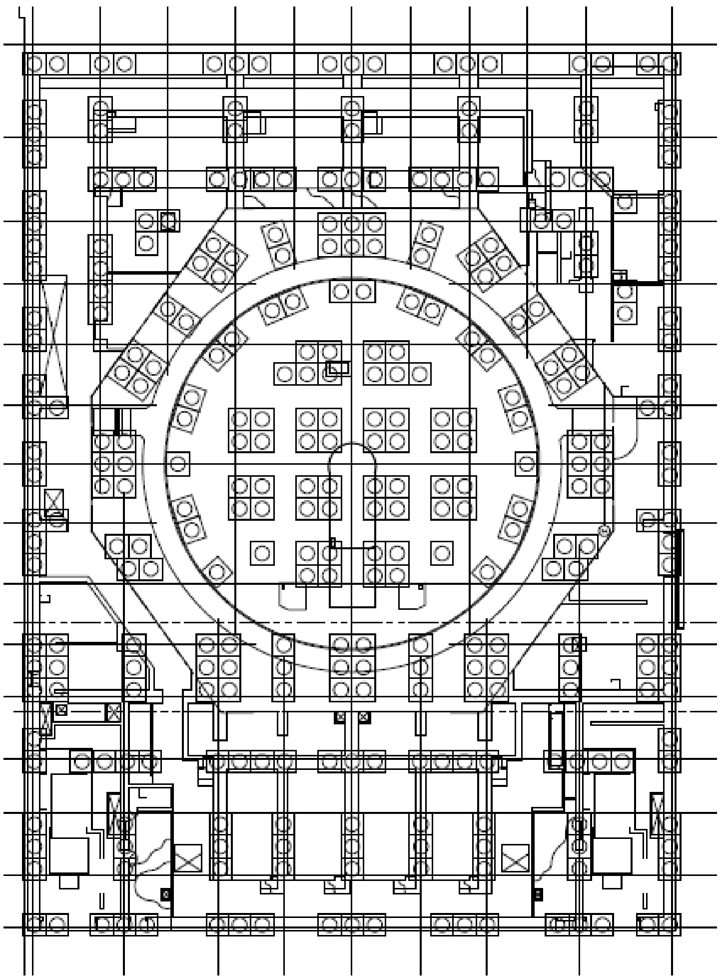


Fig. 1-4 Layout of lead rubber bearings

1.1.3 Overview of the ground condition

The ground is assumed to be rigid bedrock through which shear wave velocity of 1500m/s. Table 1-2 shows the assumed ground characteristics:

Table 1-2 Ground characteristics

Weight per unit volume ρ	Poisson's ratio ν	S wave velocity Vs	Shear modulus of elasticity G
22.6 kN/m^3	0.38	1500 m/s	5.18×10^6 kN/m^2

1.1.4 Design basis ground motion

The artificial ground motion used as the design basis ground motion has the maximum horizontal acceleration of $800cm/sec^2$ and the pseudo velocity response spectrum of 200cm/sec in the long period region (at 5% damping ratio). The vertical design basis ground motion has the maximum vertical acceleration of $536cm/sec^2$ and the pseudo velocity response spectrum of 134cm/sec in the long period region (at 5% damping ratio).

Fig. 1-5 and 1-6 show the design basis ground motion in the horizontal and vertical directions:

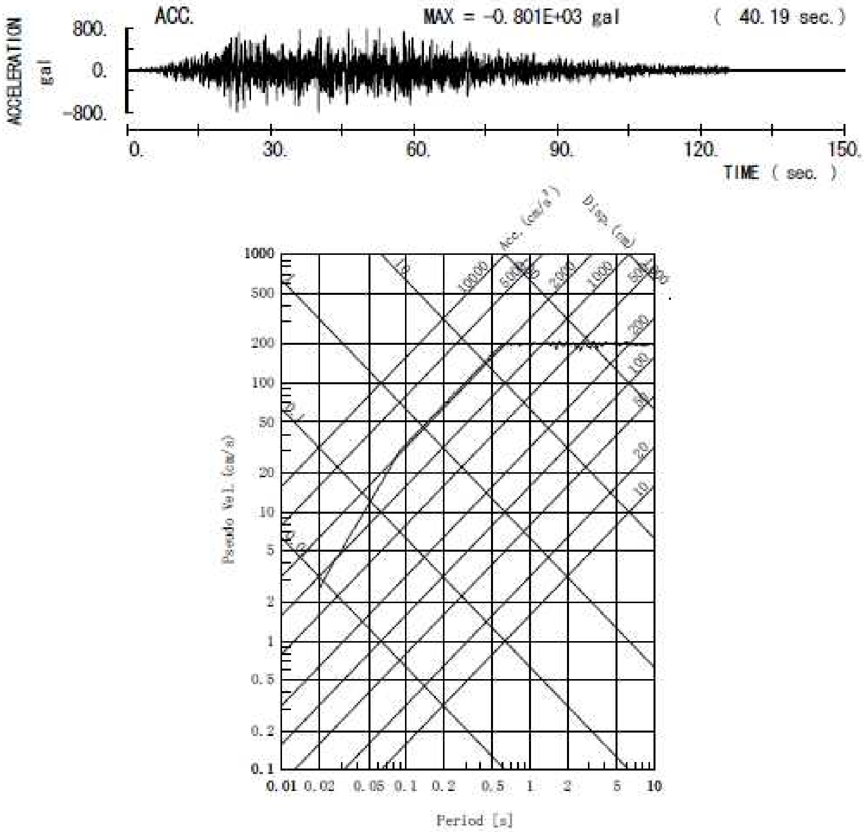


Fig. 1-5 Acceleration time history and spectrum of the design basis ground motion in the horizontal direction

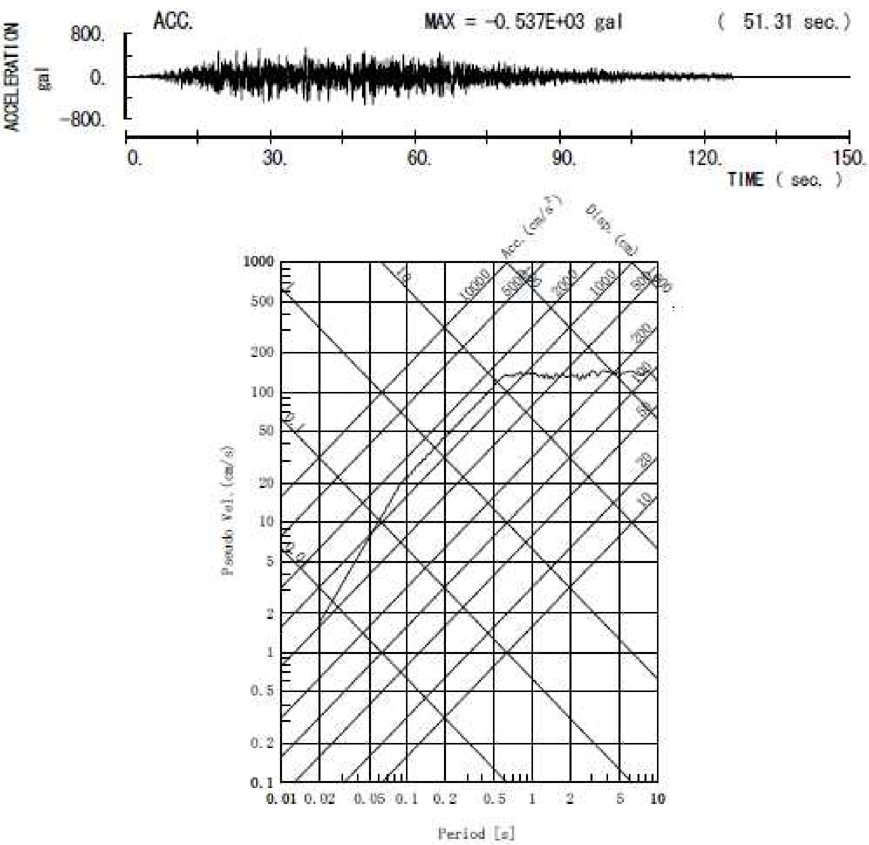


Fig. 1-6 Acceleration time history and spectrum of the design basis ground motion in the vertical direction

1.1.5 Design policy

(1) Superstructure

It is assumed that the superstructure is based on aseismic designed reactor building. The rationalization of the superstructure by applying seismic isolation is not implemented. In this design example, the superstructure design target is to ensure that the stress arising in the superstructure does not exceed the short-term allowable limit. And it is assumed that response of the superstructure is within the first turning point (elastic limit) of restoring force characteristics for the seismic reinforced concrete wall as a simple way.

(2) Seismic isolated layer

In this design example, design target of seismic isolated layer is satisfying design requirements for ensuring the integrity of components (maximum response horizontal acceleration of upper basemat and maximum response relative displacement of the seismic isolated layer). Table 1-3 shows the design targets for seismic isolated layer.

Table 1-3 Design targets for seismic isolated layer

Item	Design target
Maximum horizontal relative displacement of the seismic isolated layer	Approx. 40cm or less
Maximum horizontal response acceleration of the upper basemat	Approx. 300cm/s^2 or less

(3) Seismic isolation device

Lead rubber bearing (LRB) is chosen as the seismic isolation device because LRB also has damping characteristics so that it provides a benefit to layout design of LRB. In this design example, design requirements for ensuring the integrity of seismic isolation device should be satisfied. Table 1-4 shows the design targets for seismic isolation device.

Table 1-4 Design targets for isolation device

<table>
<tr><th colspan="2">Item</th><th>Design target</th></tr>
<tr><td rowspan="2">Maximum shear strain on the seismic isolation device</td><td>Standard characteristics</td><td>166% (1/1.5 of the linear strain limit) or less</td></tr>
<tr><td>Considering variation of characteristics*</td><td>250% (the linear strain limit) or less</td></tr>
<tr><td>Tensile pressure on the seismic isolation device</td><td colspan="2">1N/mm^2 or less</td></tr>
</table>

＊ Characteristics variation caused by variations of products, aging and environment temperature condition.

(4) Horizontal clearance

Horizontal clearance is 150cm for ensuring horizontal distance which is larger than ultimate displacement of the seismic isolation device.

1.1.6 Seismic response analysis

(1) Model for the seismic response analysis in the horizontal direction

a. Seismic response analysis model

Fig. 1-7 illustrates the horizontal seismic response analysis model. Table 1-5 explains the modeling of the seismic isolation device. The model considers the ground motion in the E-W direction because E-W direction is dominant in seismic design in this case.

In this seismic response analysis model, the superstructure is represented as a multiple lumped mass model (including the steel frame structure represented by an equivalent shearing bar element) in consideration of the nonlinearity. The seismic isolated layer is represented using horizontal and vertical springs in consideration of the nonlinearity of response to horizontal and rocking motions. In addition, interactions with the soil are considered using soil spring under lower basemat.

Table 1-5 Analysis model of seismic isolation device (horizontal)

Motion type	Object	Model	Remarks
Horizontal	Laminated rubber bearing	Nonlinear horizontal spring	- The whole seismic isolated layer is represented by a single horizontal spring. - Hardening characteristics is considered in the nonlinear spring
	Lead plug	Nonlinear horizontal spring	- The whole seismic isolated layer is represented by a single horizontal spring.
Rocking	Laminated rubber bearing	Nonlinear vertical spring	- The whole seismic isolated layer is modeled as a group of multiple vertical springs. - The springs are laid out in the horizontal direction, enabling the evaluation of how the axial force acting on the seismic isolation device changes in response to the rocking motion.

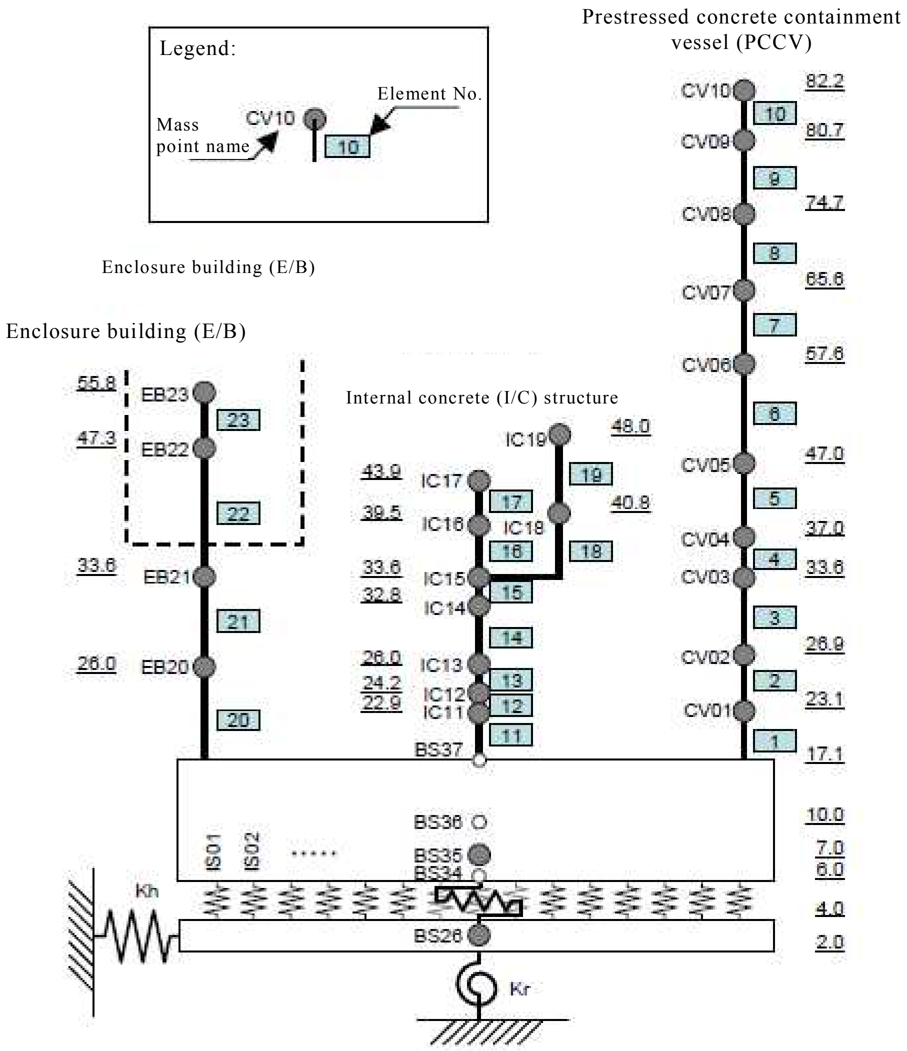
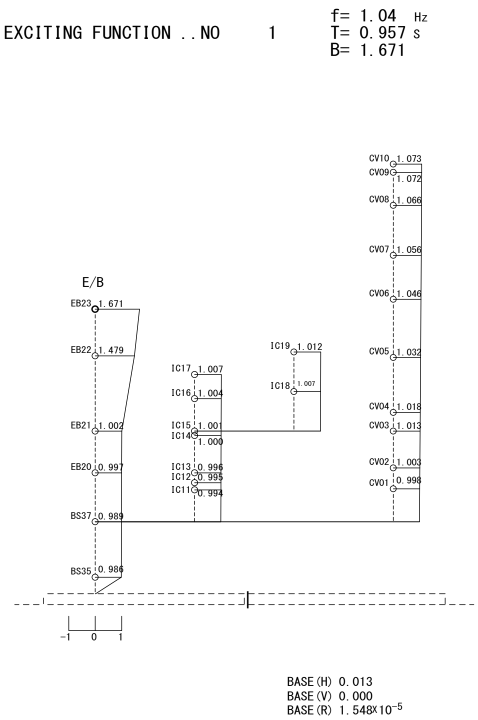


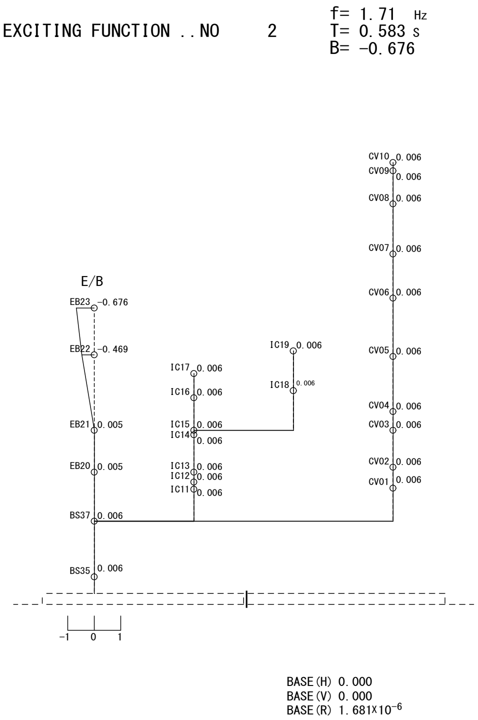
Fig. 1-7 Seismic response analysis model of PWR seismic isolated building in the horizontal direction (E-W)

b. Eigenvalue analysis

The seismic isolation device (lead rubber bearing) has a nonlinear restoration force characteristic (a bilinear type) in the horizontal direction. Therefore, the eigenvalue analysis is conducted using the primary stiffness before the yielding of lead plug. Figs. 1-8 and 1-9 show the results of eigenvalue analysis. In the horizontal direction, the vibration mode unique to horizontal isolation, associated with the rigid body displacement of the superstructure, is dominant. In the higher order modes, the participation function values of those vibration modes are small.

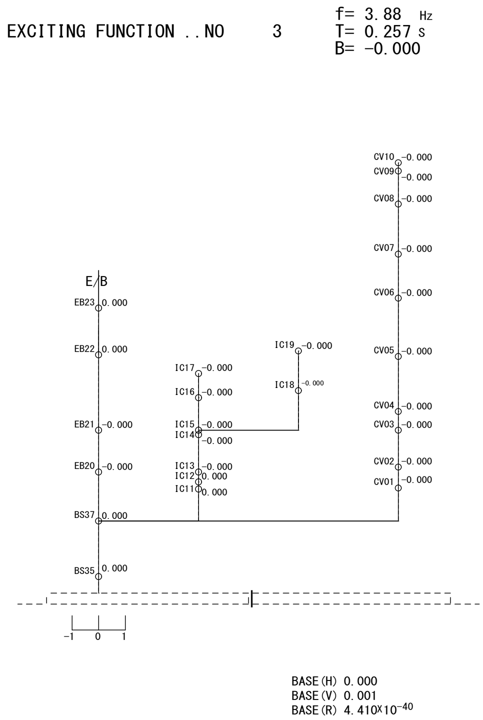


a. 1st modal participation function

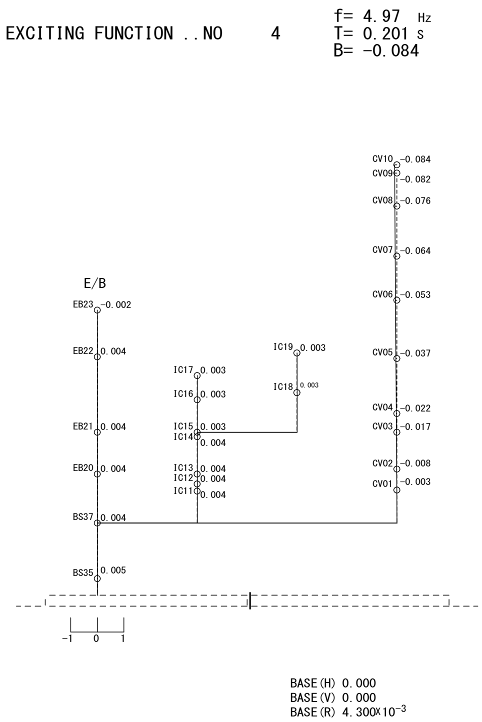


b. 2nd modal participation function

Fig. 1-8 1st and 2nd modal participation functions in the horizontal direction from the eigenvalue analysis



c. 3rd modal participation function



d. 4th modal participation function

Fig. 1-9 3rd and 4th modal participation functions in the horizontal direction from the eigenvalue analysis

(2) Model for the seismic response analysis in the vertical direction

a. Seismic response analysis model

Fig. 1-10 illustrates the vertical seismic response analysis model. Table 1-6 explains the modeling of the seismic isolation device.

In this seismic response analysis model, the superstructure is represented a multiple lumped mass model with axial bar elements which correspond to the estimated stiffness of structures such as shear walls. In addition, interactions with the soil are considered using vertical ground spring under lower basemat.

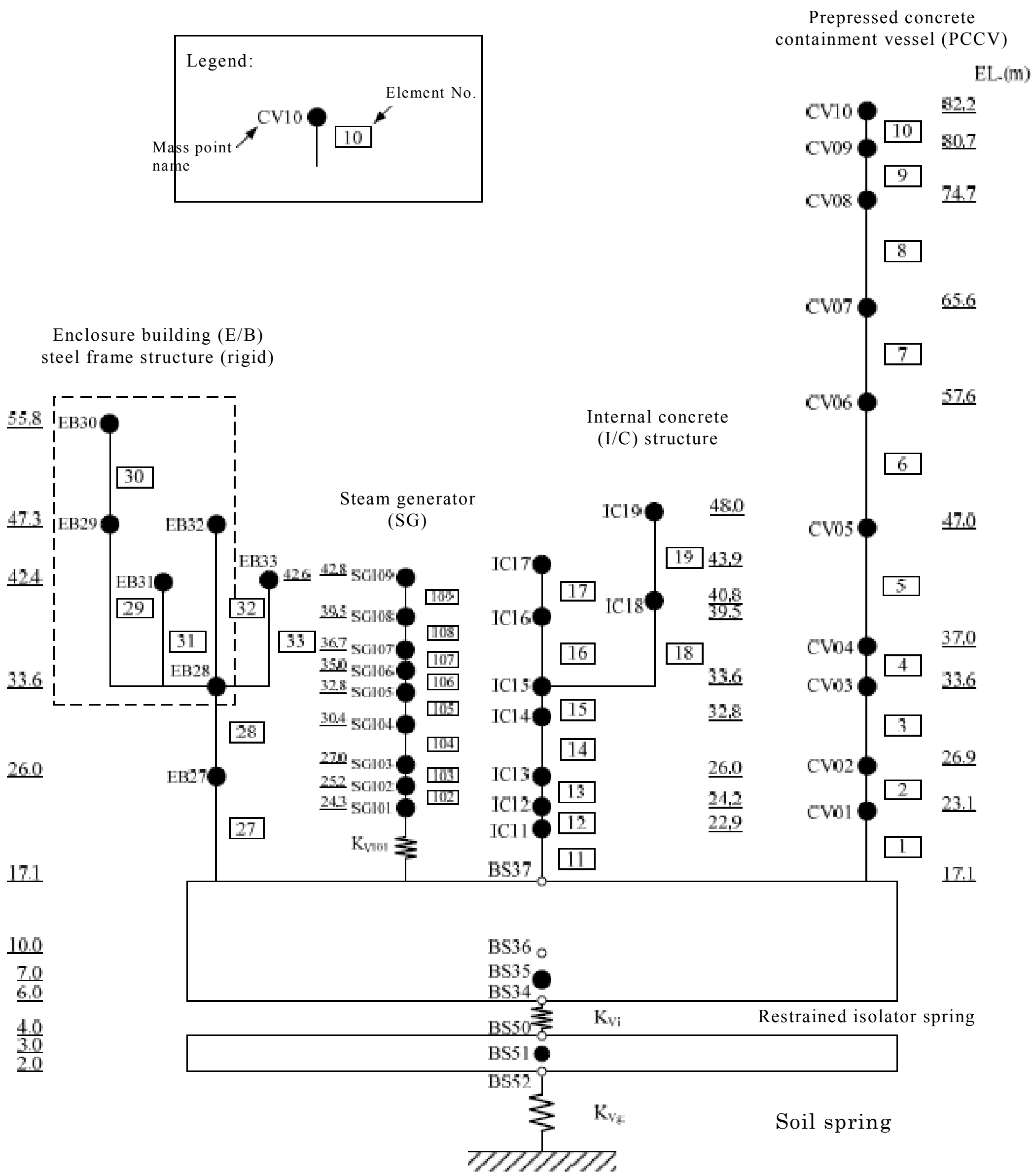


Fig 1-10 Model for the seismic response analysis of PWR seismic isolated building in the vertical direction

Table 1-6 Analysis model of seismic isolation device (vertical)

Motion type	Object	Model	Remarks
Vertical	Laminated rubber bearing	Nonlinear vertical spring	- The whole seismic isolated layer is represented by a single spring. - The model is able to evaluate changes of the axial force working on the seismic isolation device.
	Lead plug	Excluded from the scope of modeling	

b. Eigenvalue analysis

The seismic isolation device (lead rubber bearing) has a nonlinear restoration force characteristic in the vertical direction. The axial stiffness of the bearing differs by whether it is in compressive region or tensile region. Therefore, the eigenvalue analysis is conducted using the value of compressive stiffness.

Fig. 1-11 and Fig. 1-12 show the results of eigenvalue analysis.

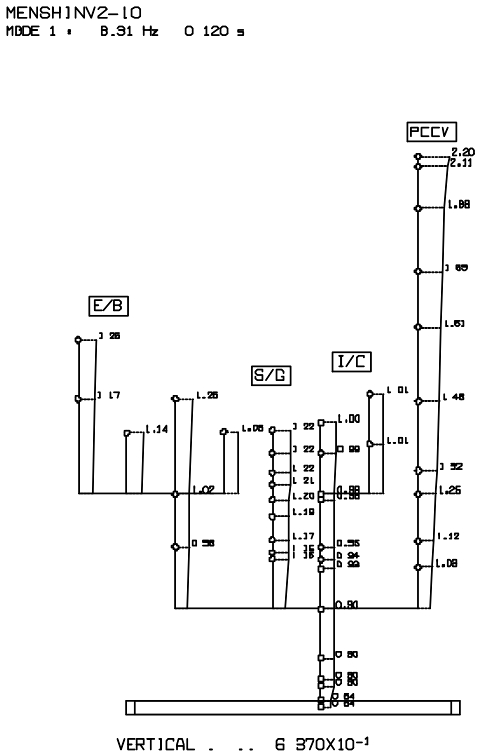
(3) Variations of characteristics of seismic isolation device

In seismic response analysis, variations of horizontal characteristics in the seismic isolation device are considered (variations originating in the manufacturing process, variations caused by aging and the environment temperature). Table 1-7 shows variations of horizontal characteristics as a degree of variability to standard characteristics used in the trial design.

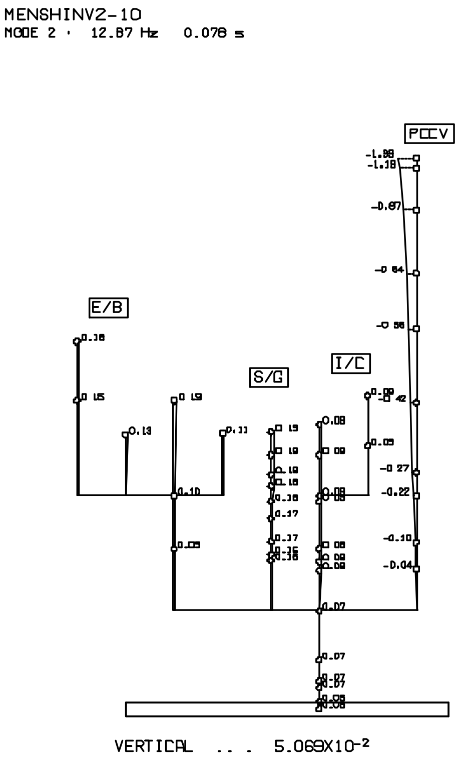
Table 1-7 Variations of characteristics of seismic isolation device

Horizontal direction			
Variation in the negative side		Variation in the positive side	
Rubber stiffness	Yield load of lead	Rubber stiffness	Yield load of lead
-15%	-20%	+35%	+30%

- Negative variation: In case of decreasing stiffness of rubber and yield load of lead caused by variation of products, aging and environment temperature.
- Positive variation: In case of increasing stiffness of rubber and yield load of lead caused by variation of products, aging and environment temperature.

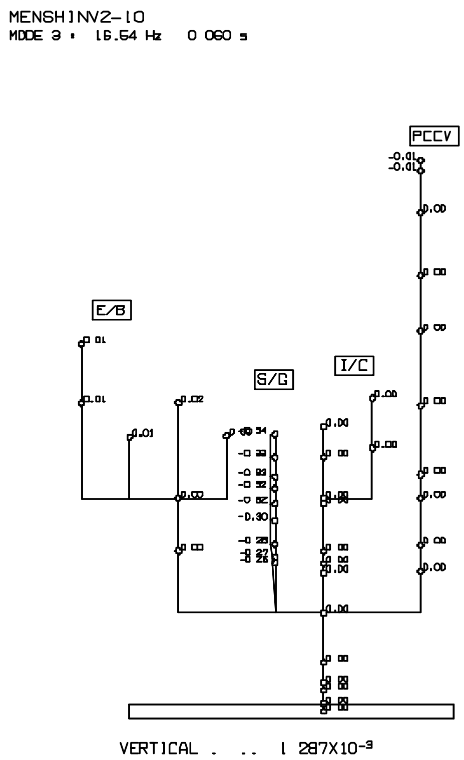


a. 1st modal participation function

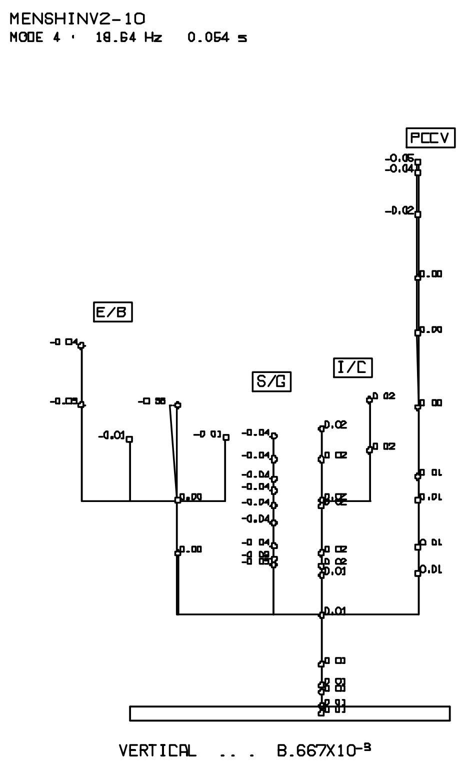


b. 2nd modal participation function

Fig. 1-11 1st and 2nd modal participation functions in the vertical direction from the eigenvalue analysis



c. 3rd modal participation function



d. 4th modal participation function

Fig. 1-12 3rd and 4th modal participation functions in the vertical direction from the eigenvalue analysis

(4) Seismic response analysis results

a. Result of seismic response analysis in the horizontal direction

Figs. 1-13 and 1-14 show the distributions of the maximum response values of acceleration, displacement, shear stress and shear strain. The maximum acceleration of the upper basemat is significantly smaller than that of the input ground motion (800cm/sec^2).

Table 1-8a shows the maximum shear strain of the reactor building (variations in the seismic isolation device is considered). The maximum response shear strain is much lower than the design target. Therefore it is expected that the stress to each structural element in the reactor building would be smaller than the short-term allowable limit.

Table 1-8b shows maximum response values of seismic isolated layer. Those results meet the design target of the seismic isolated layer.

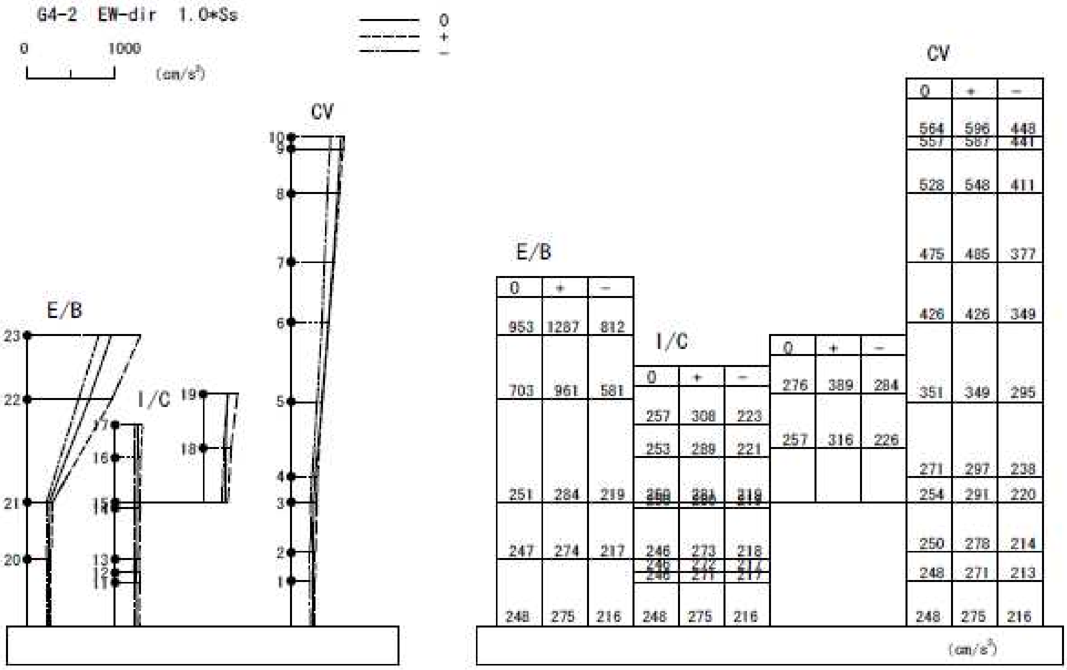
Table 1-8a Maximum shear strain of the reactor building

	Design target*	Response result		
		Standard characteristics	Variation in the positive side	Variation in the negative side
Prepressed concrete containment vessel (PCCV)	353×10^{-6} or less	88×10^{-6}	92×10^{-6}	72×10^{-6}
Internal concrete (I/C) structure	182×10^{-6} or less	26×10^{-6}	30×10^{-6}	23×10^{-6}
Enclosure building (E/B)	174×10^{-6} or less	36×10^{-6}	41×10^{-6}	31×10^{-6}

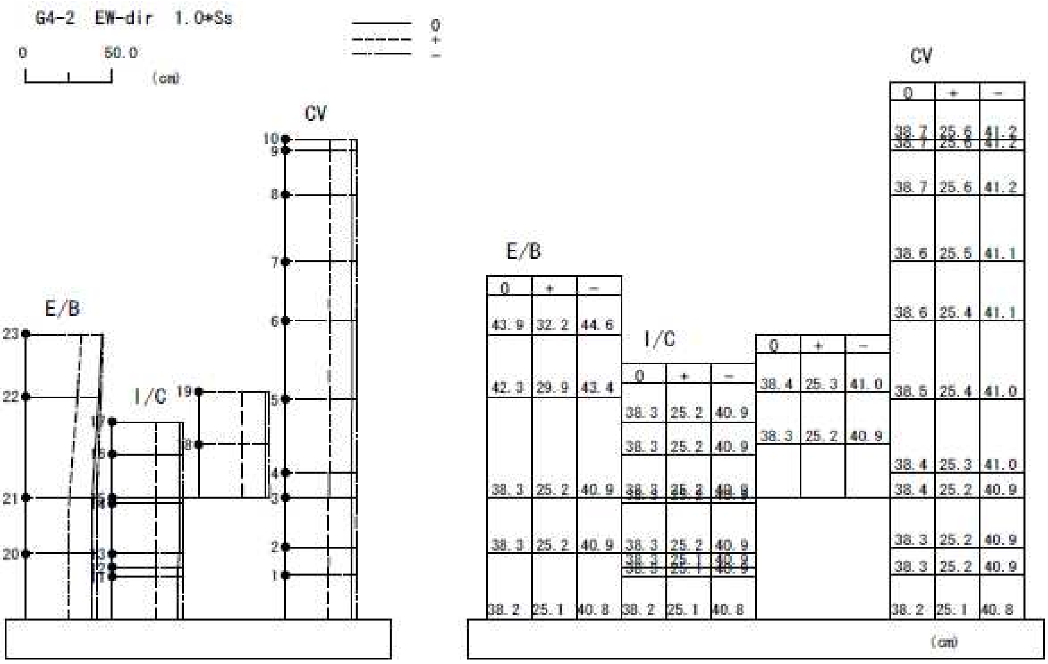
∗ Within the shear crack point in the restoring force characteristics curve of reinforced concrete shear wall

Table 1-8b Maximum response values of seismic isolated layer

	Design target	Response result		
		Standard characteristics	Variation in the positive side	Variation in the negative side
Maximum relative displacement of the seismic isolated layer (cm)	Approx. 40 or less	38.2	25.1	40.8
Maximum response acceleration of the upper basemat (cm/s^2)	Approx. 300 or less	248	275	216



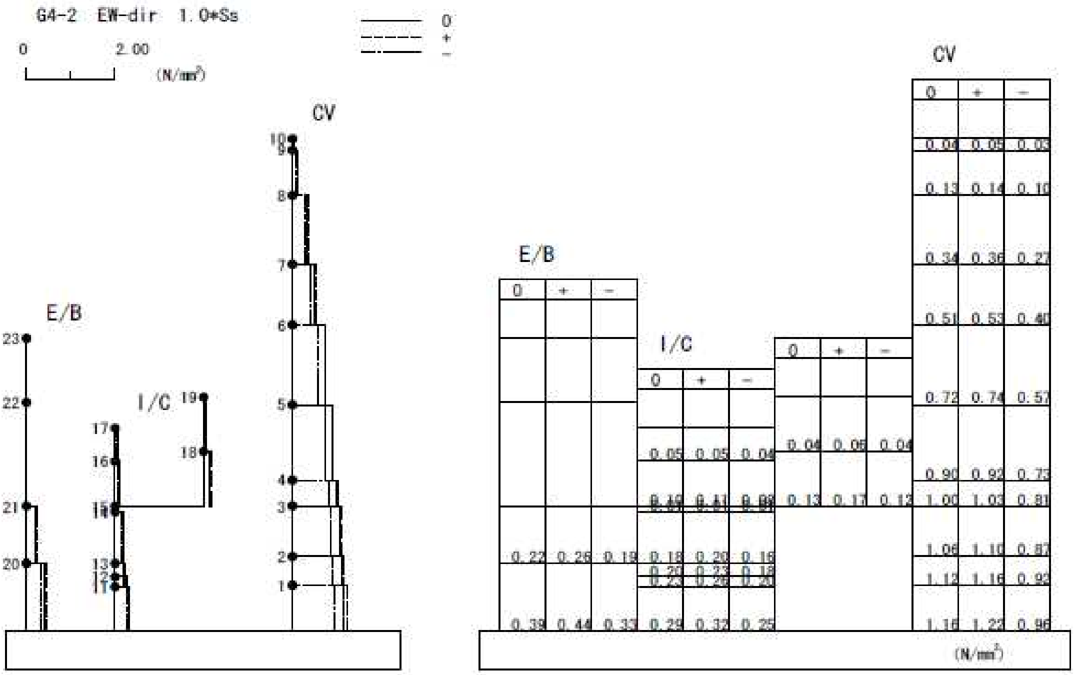
a. Distributions of the maximum response acceleration



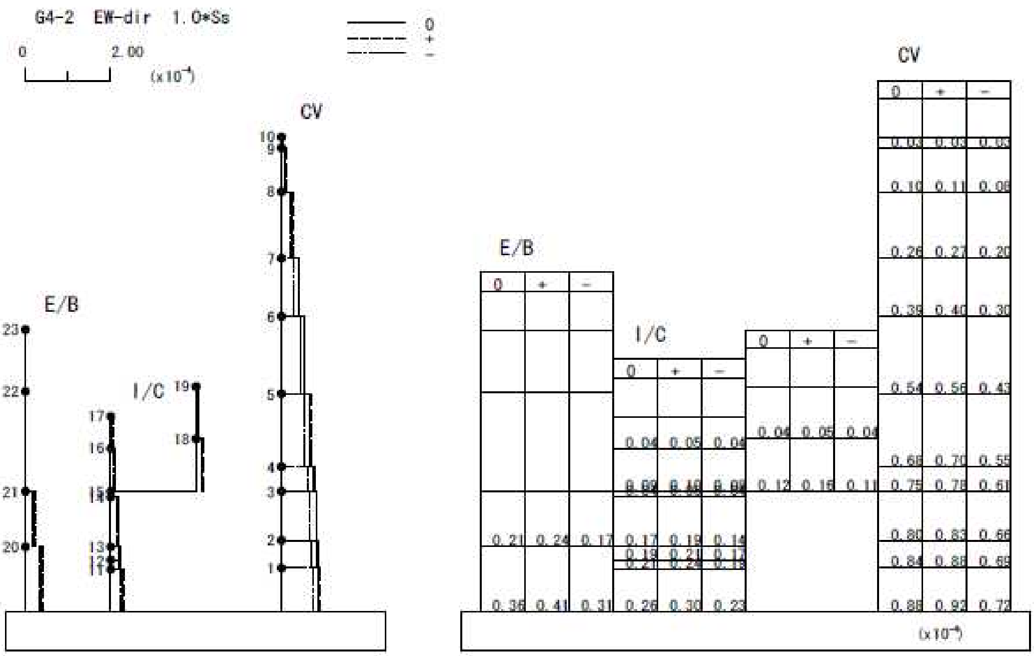
b. Distributions of the maximum response displacement

(Standard characteristics are represented as 0. Variation in the positive side is represented as +. Variation in the negative side is represented as -.)

Fig. 1-13 Response results of superstructure (maximum acceleration and maximum displacement)



a. Distributions of the maximum shear stress



MA〉 b. Distributions of the maximum shear strain

(Standard characteristics are represented as 0. Variation in the positive side is represented as +. Variation in the negative side is represented as -.)

Fig. 1-14 Response results of superstructure (maximum shear stress and maximum shear strain)

b. Result of seismic response analysis in the vertical direction

Figs. 1-15 and 1-16 show the distributions of the maximum response acceleration and axial force of superstructure. The maximum response acceleration of the upper basemat is slightly higher than the maximum acceleration of the input ground motion (536cm/sec^2).

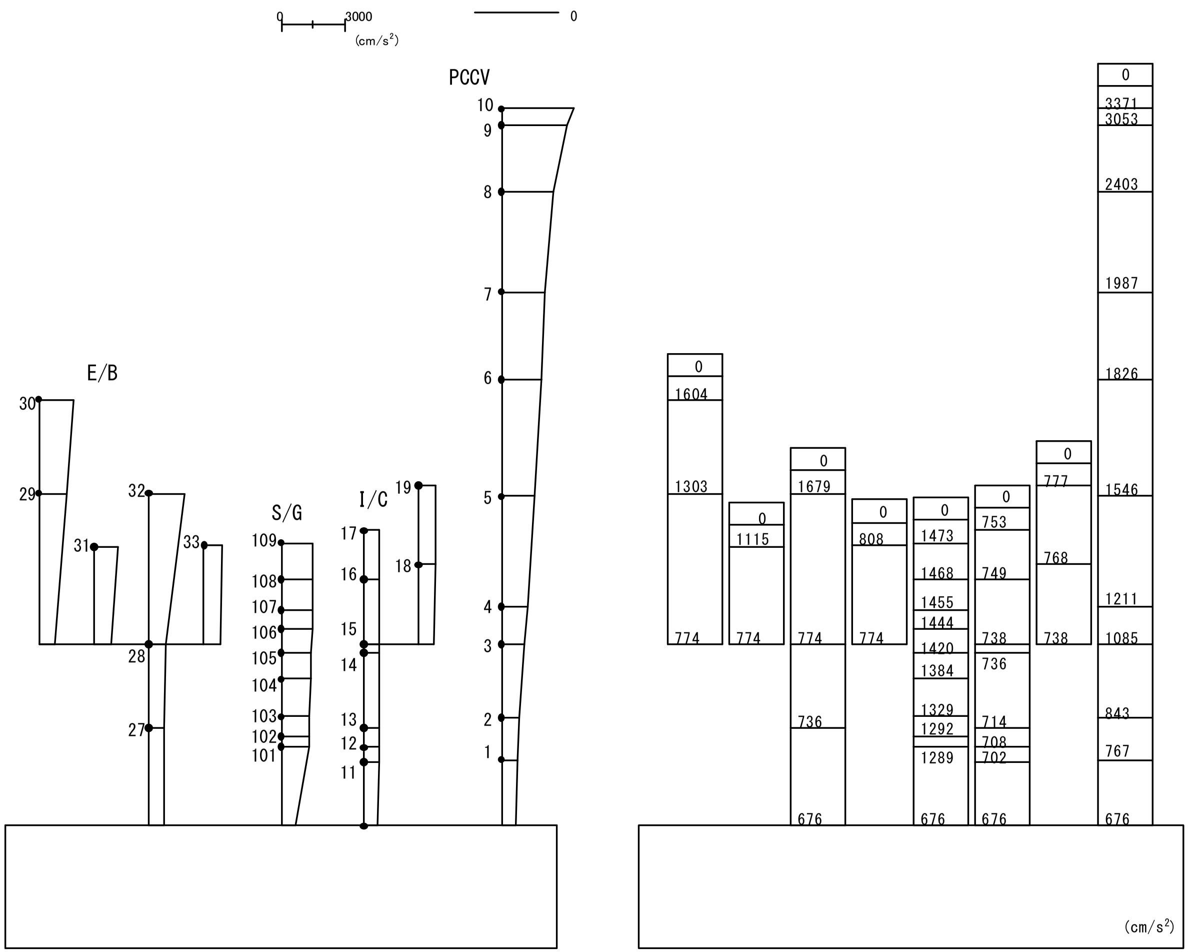


Fig. 1-15 Distributions of the maximum response vertical acceleration of superstructure

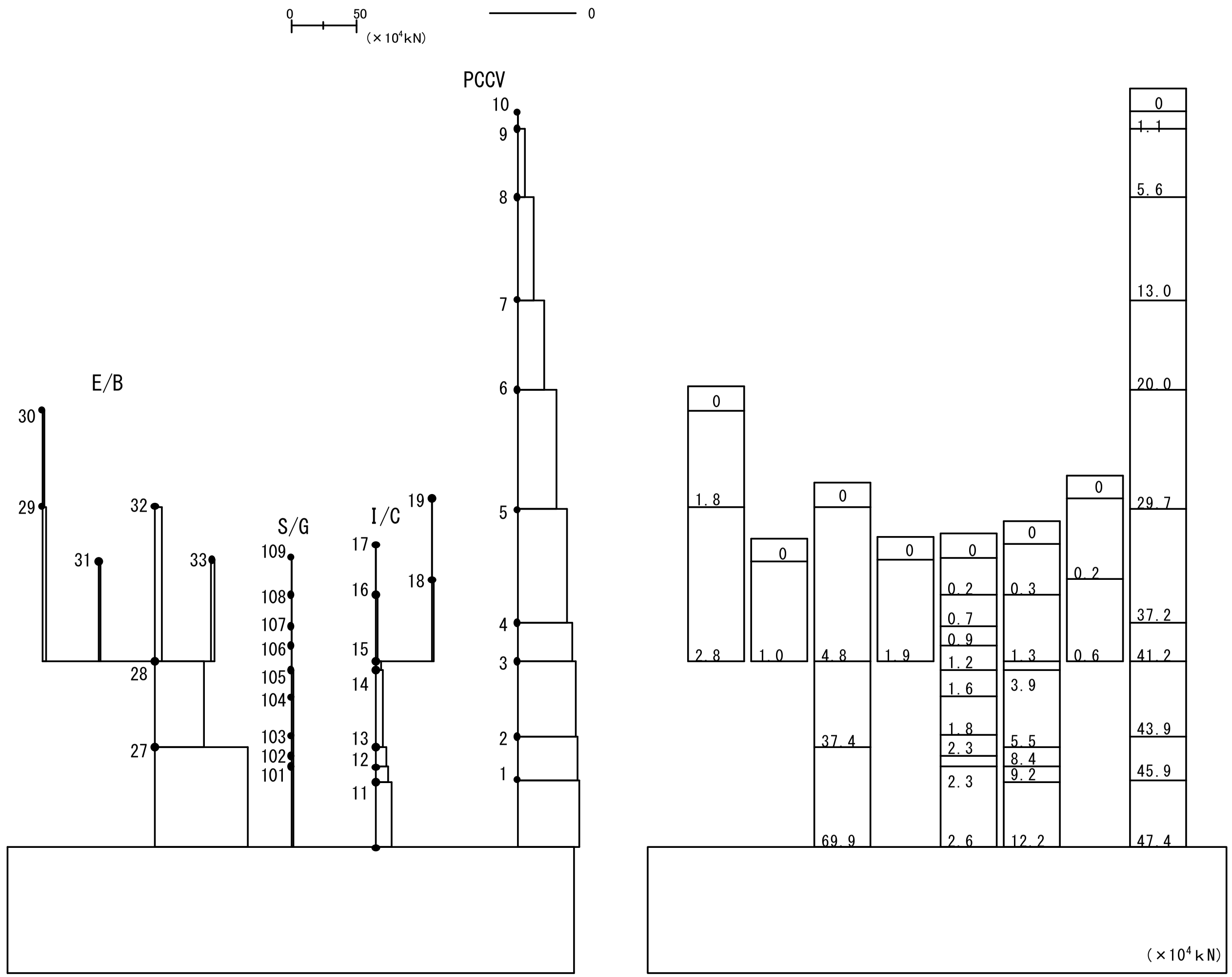


Fig. 1-16 Distributions of the maximum response axial force of superstructure

1.1.7 Verification of design of the seismic isolation device

Table 1-9 reproduces the design targets for seismic isolation device (the lead rubber bearing):

Table 1-9 Design targets of seismic isolation device

Item	Design target	
Shear strain of seismic isolation device	Standard characteristics	Not exceed 166% (1/1.5 of the linear strain limit)
	Considering variation of characteristics*	Not exceed 250% (the linear strain limit)
Tensile pressure to seismic isolation device	not exceed 1 N/mm^2	

∗ In case of characteristics variation caused by variations of products, aging and environment temperature.

(1) Maximum shear strain of seismic isolation device

Table 1-10 shows the maximum shear strain on the seismic isolation device due to the design basis ground motion. Assuming the standard characteristics values, the maximum strain on the seismic isolation device is expected to be 159%, which meets the design target of not to allow the strain to go above 166%. Even when the variations of characteristics are considered, the maximum strain is expected to be sufficiently lower than 250% as the design target.

Table 1-10 Maximum shear strain of seismic isolation device

	Response result		
	Standard characteristics	Variation in the positive side	Variation in the negative side
Maximum shear strain (total rubber thickness: 24cm)	159% (38.2cm)*	105% (25.2cm)*	170% (40.8cm)*
Design target	166% or less	250% or less	

∗( ) is represented as maximum relative displacement of seismic isolation device.

(2) Axial pressure of seismic isolation device

Table 1-11 shows long-term axial pressure on the seismic isolation device and the maximum axial pressure on the seismic isolation device considering the variation of seismic isolation device by each (horizontal and vertical) ground motion direction along with the absolute sum of them. The tensile pressure on the seismic isolation device was found to be lower than 1.0N/mm^2. The result of evaluation demonstrates compliance with the design target.

Table 1-11 Result of evaluation of tensile pressure on seismic isolation device

(N/mm^2)	Horizontal characteristics of seismic isolation device		
	Standard characteristics	Variation in the positive side	Variation in the negative side
Long-term axial pressure	-5.25		
Axial pressure fluctuation by the sole input of the horizontal ground motion	1.54	1.80	1.34
Axial pressure fluctuation by the sole input of the vertical ground motion	3.93		
Evaluation of tensile pressure (Absolute value sum method)	0.22	0.48	0.02

∗ In the representation of axial pressure, a negative value indicates a compressive pressure.

1.1.8 Conclusion

This section reviewed a PWR seismic isolated building, describing in particular the trial design of seismic isolation device. The results of seismic response analysis, conducted using the design basis ground motion as the input, demonstrated conformity with the design target values.

1.2 Common Foundation Type Seismic Isolation Building Design for BWR

1.2.1 Introduction

The reactor building is a rigid structure mainly consisted of box frame type reinforced concrete. Therefore, the implementation of seismic isolated structural design to the reactor building is expected to ensure significant isolation effect because of a large difference between the natural period specific to the seismic isolation device and that of building structures, contributing greatly to the improvement of seismic safety.

This section provides an example of seismic isolated building design at a boiling water reactor (BWR) plant where the reactor building, control building and turbine building stand on a common seismic isolated foundation mat (hereinafter, “BWR common foundation type seismic isolation building”). In the case of the BWR common foundation type seismic isolation building, the connecting piping which runs between the reactor building and the turbine building is also seismically isolated. Therefore, this common foundation design is more advantageous than the seismic isolation only of the reactor building that would require the main steam piping and other high temperature and high pressure piping running between seismic isolated and non-isolated buildings to take measures to absorb relative displacements. In this example, the superstructure is aseismic building of advanced BWR, not the one rationalized by seismic isolated design. In this trial design example, the seismic isolation devices were designed and response results of those devices were confirmed to meet criteria by seismic response analysis.

1.2.2 Overview of the building

In this example, the BWR common foundation type seismic isolation building is consisted of reinforced concrete structures, steel frame structures and steel framed reinforced concrete structures, and has the basemat of approximately 126m x 129m and the height of about 64m (from the lower foundation mat to the top of the reactor building). The total weight of the base-isolated structures amounts to about 5,660,000kN. The seismic isolated foundation supports a reactor building, a control building and a turbine building. The foundation is a mat foundation of reinforced concrete. Lead rubber bearing (Shear modulus of elasticity of rubber is 0.392N/mm^2 at 15 degree C) is used as the seismic isolation device.

Figs. 1-17 and 1-18 show the overview of sectional view and planar view of the BWR common foundation type seismic isolation building. Table 1-12 lists the specifications of lead rubber bearing. Figs. 1-19 and 1-20 show the design and layout of lead rubber bearings.

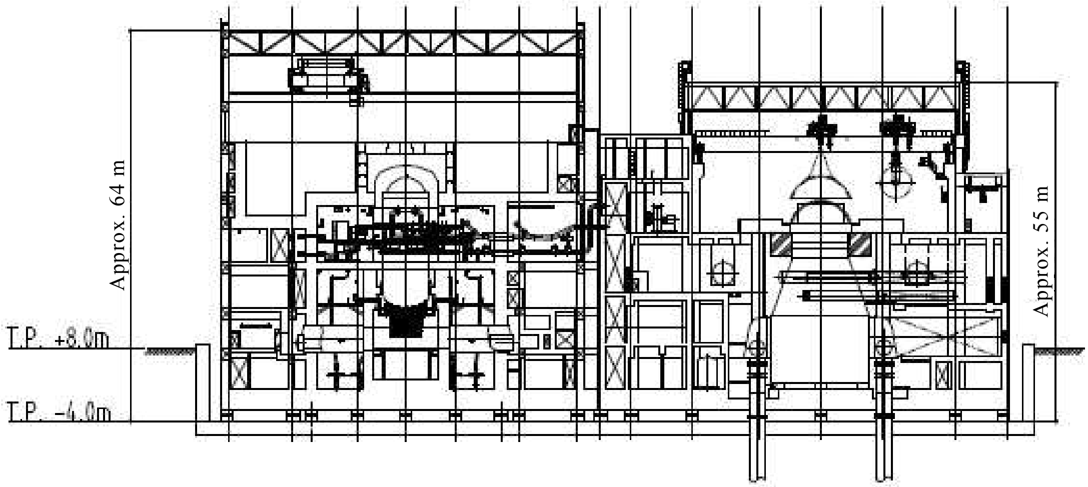


Fig. 1-17 Overview of sectional view of BWR common foundation type seismic isolation building
(Locations of the seismic isolation devices are tentative)

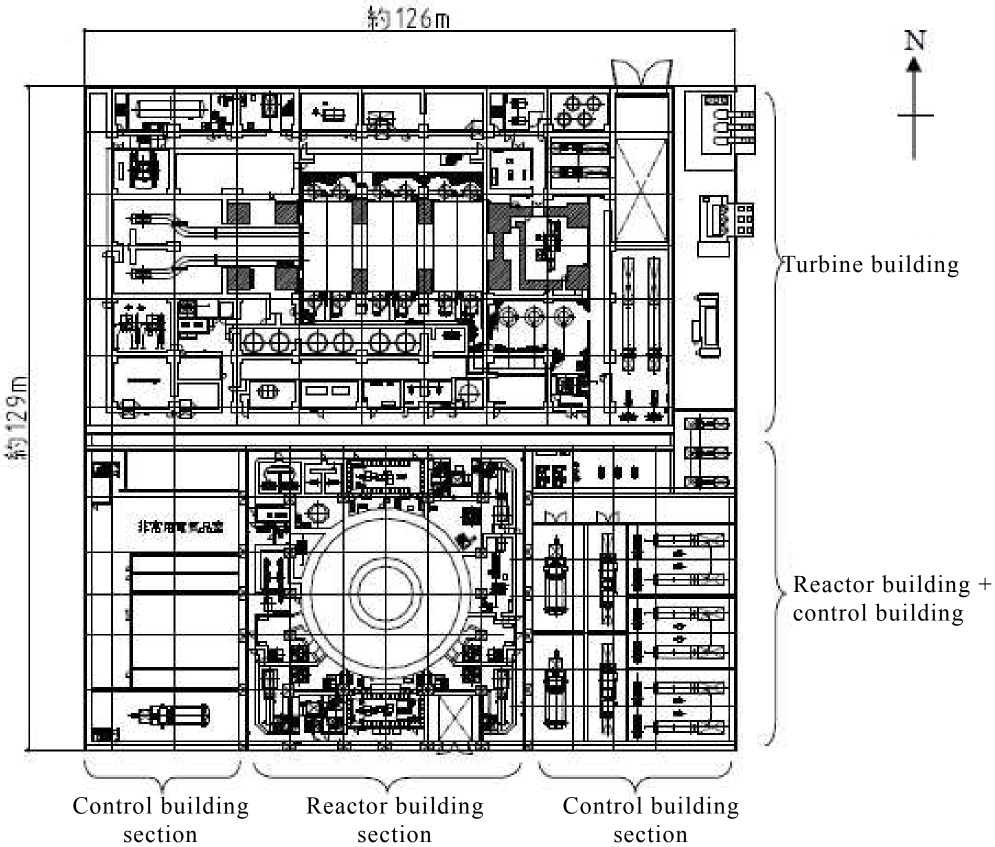


Fig. 1-18 Overview of planar view of BWR common foundation type seismic isolation building

Table 1-12 Specifications of lead rubber bearing

	Specifications		Rubber type: G4
Dimensions	Outside diameter (D)	(mm)	1600
	Lead plug diameter (Dp)	(mm)	392
	Rubber thickness per layer (tr)	(mm)	10
	Number of rubber layers (n)		26
	Total rubber height (Hr)	(mm)	260
	Steel plate thickness per layer	(mm)	6.8
	Number of steel plate layers		25
	Total thickness including rubber and steel plate thickness (Hp)	(mm)	430
	Primary shape coefficient S1 = D/4tr		40.0
	Secondary shape coefficient S2 = D/Hr		6.2
	Rubber plug height/diameter ratio (Hp/Dp)		1.10
Linear limit in the horizontal direction	Linear strain limit		2.5
	Linear displacement limit	(mm)	650
	Linear displacement limit / 1.5	(mm)	433
Bearing load and required number of lead rubber bearings	Bearing load (P)	(kN)	9000
	Weight of the superstructure(W)	(MN)	5660
	Number of lead rubber bearing		629
	Long-term axial pressure	(N/mm^2)	4.76
Vibration characteristics	Horizontal period at the secondary stiffness Kh	(sec)	3.41
	Natural frequency in the vertical direction	Hz）	16.29
	Yield seismic intensity		0.121
	Remarks	- bearing load: 9000kN - The lead plug sectional area is 1.5 times of standard products available in the market.	

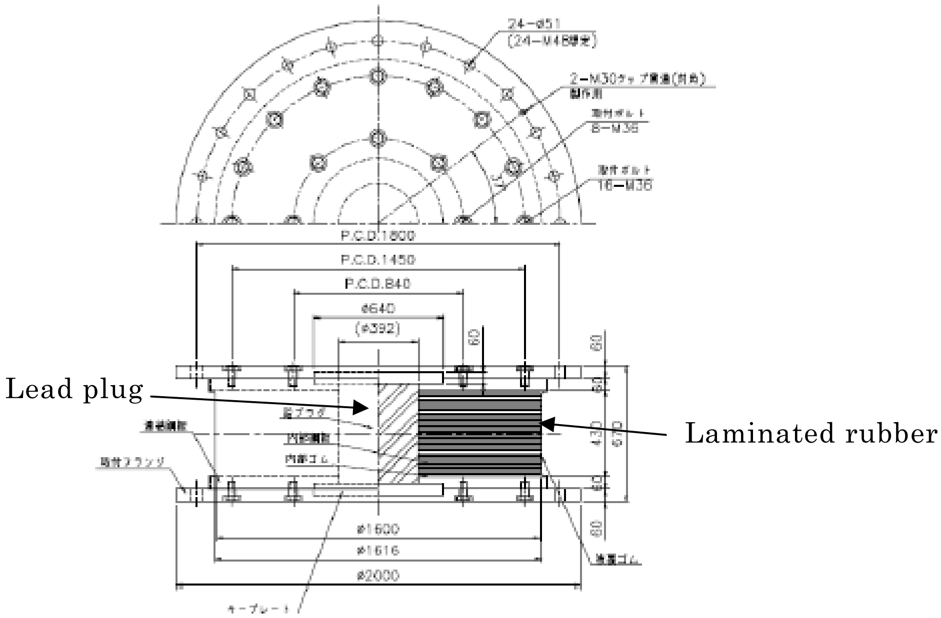


Fig. 1-19 Design of lead rubber bearing

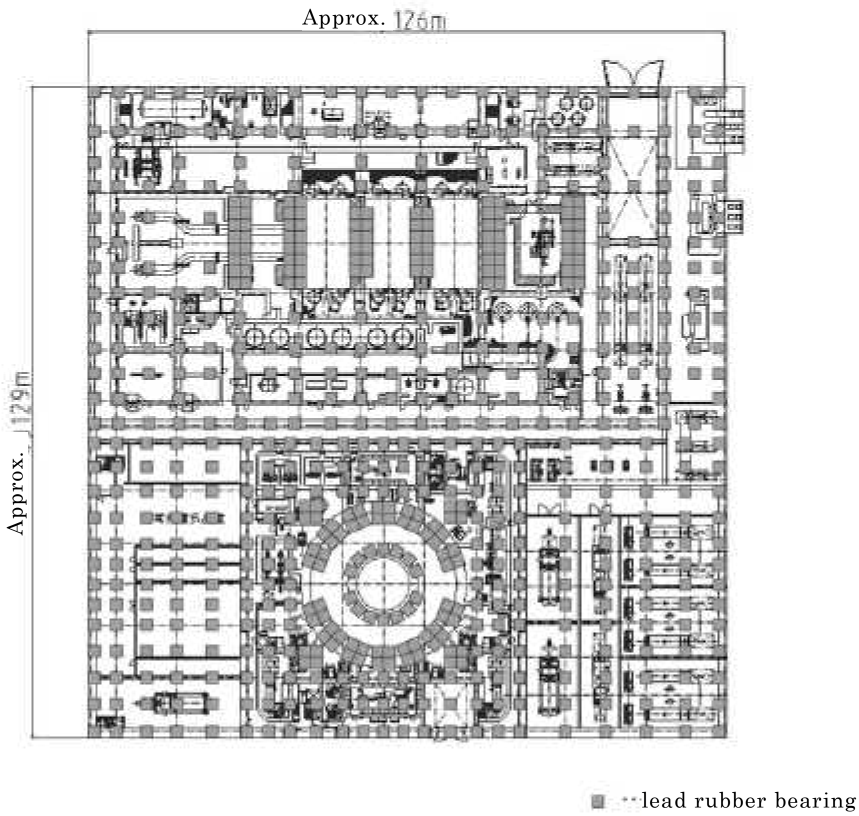


Fig. 1-20 Layout of lead rubber bearings

1.2.3 Overview of the ground condition

The ground is assumed to be soft soil of which shear wave velocity of 700m/s. Table 1-13 shows the assumed ground characteristics:

Table 1-13 Ground characteristics

Weight per unit volume ρ	Poisson's ratio ν	S wave velocity Vs	Shear modulus of elasticity G
20.3 kN/m^3	0.42	700 m/s	1.01×10^6 kN/m^2

1.2.4 Design basis ground motion

The artificial ground motion used as the design basis ground motion has the maximum horizontal acceleration of 800cm/sec^2 and the pseudo velocity response spectrum of 200cm/sec in the long period region (at 5% damping ratio). The vertical design basis ground motion has the maximum vertical acceleration of 533cm/sec^2 and the pseudo velocity response spectrum of 153cm/sec in the long period region (at 5% damping ratio).

Fig. 1-21 and 1-22 show the design basis ground motion in the horizontal and vertical directions:

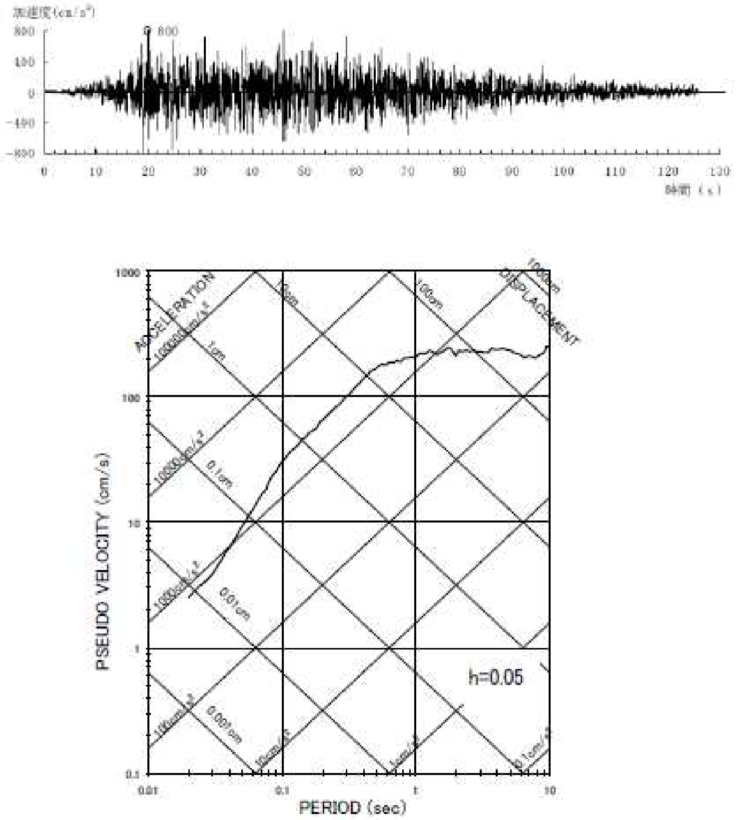


Fig. 1-21 Acceleration time history and spectrum of the design basis ground motion in the horizontal direction

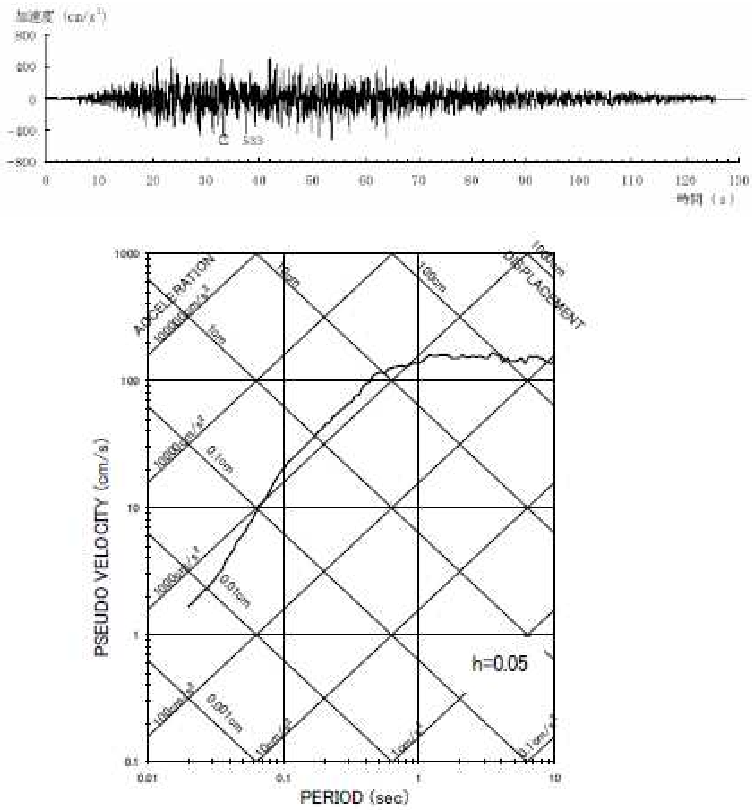


Fig. 1-22 Acceleration time history and spectrum of the design basis ground motion in the vertical direction

1.2.5 Design policy

(1) Superstructure

The superstructure is based on aseismic design, and the rationalization of the superstructure by applying seismic isolation is not implemented. In this design example, the superstructure design target is to ensure that the stress arising in the superstructure does not exceed the short-term allowable limit. And it is assumed that response of the superstructure is within the shear crack point of restoring force characteristics for the seismic reinforced concrete wall as an easy way.

(2) Seismic isolated layer

In this design example, design target of seismic isolated layer is satisfying design requirements for ensuring the integrity of components (maximum response horizontal acceleration of upper basemat and maximum response relative displacement of the seismic isolated layer). Table 1-14 shows the design targets for seismic isolated layer.

Table 1-14 Design target for seismic isolated layer

Item	Design target
Maximum horizontal relative displacement of the seismic isolated layer	Approx. 60cm or less
Maximum horizontal response acceleration of the upper basemat	Approx. $300 cm/s^2$ or less

(3) Seismic isolation device

Lead rubber bearing (LRB) is chosen as the seismic isolation device because LRB also has damping characteristics so that it provides a benefit to layout design of LRB. In this design example, design requirements for ensuring the integrity of seismic isolation device should be satisfied. Table 1-15 shows the design targets for seismic isolation device.

Table 1-15 Design targets for seismic isolation device

<table>
<tr><th colspan="2">Item</th><th>Design target</th></tr>
<tr><td rowspan="2">Maximum shear strain on the seismic isolation device</td><td>Standard characteristics</td><td>166% (1/1.5 of the linear strain limit) or less</td></tr>
<tr><td>Considering variation of characteristics*</td><td>250% (the linear strain limit) or less</td></tr>
<tr><td>Tensile pressure on the seismic isolation device</td><td colspan="2">$1 N/mm^2$ or less</td></tr>
</table>

* characteristics variation caused by variations of products, aging and environment temperature condition.

(4) Horizontal clearance

Horizontal clearance is 200cm for ensuring horizontal distance which is larger than ultimate displacement of the seismic isolation device.

1.2.6 Seismic response analysis

(1) Model for the seismic response analysis in the horizontal direction

a. Seismic response analysis model

Fig. 1-23 illustrates the horizontal seismic response analysis model. Table 1-16 explains the modeling of the seismic isolation device. The model captures a profile along a line in the N-S direction because N-S direction is dominant in seismic design in this trial case.

In this seismic response analysis model, the superstructure is represented as a multiple lumped mass model (including the steel frame structure represented by an equivalent shearing bar element) in consideration of the nonlinearity. The seismic isolated layer is represented using horizontal and vertical springs in consideration of the nonlinearity of response to horizontal and rocking motions. In addition, interactions with the soil are considered using soil spring under lower basemat .

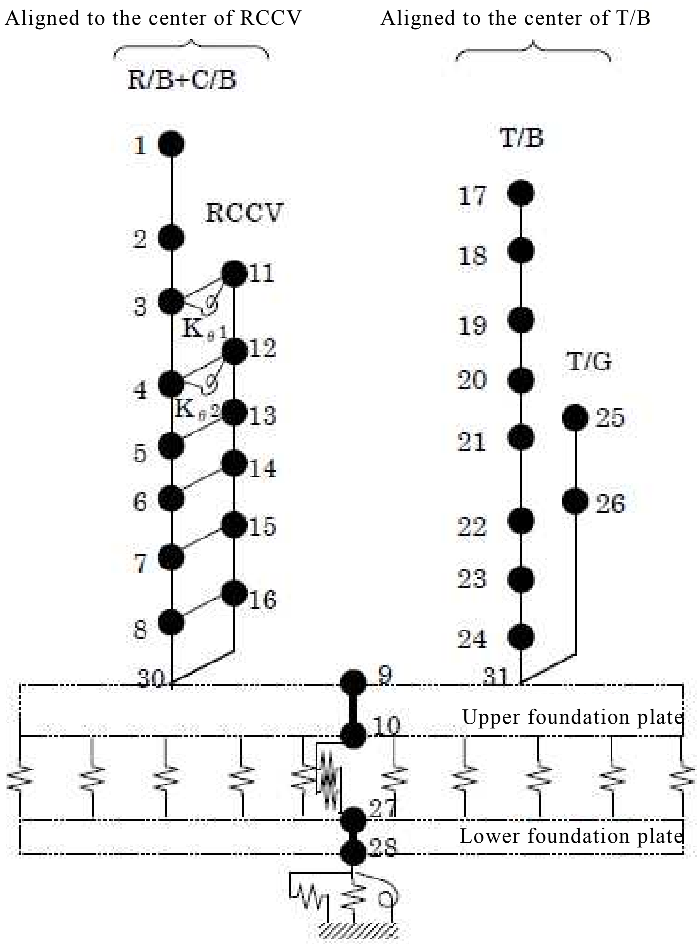


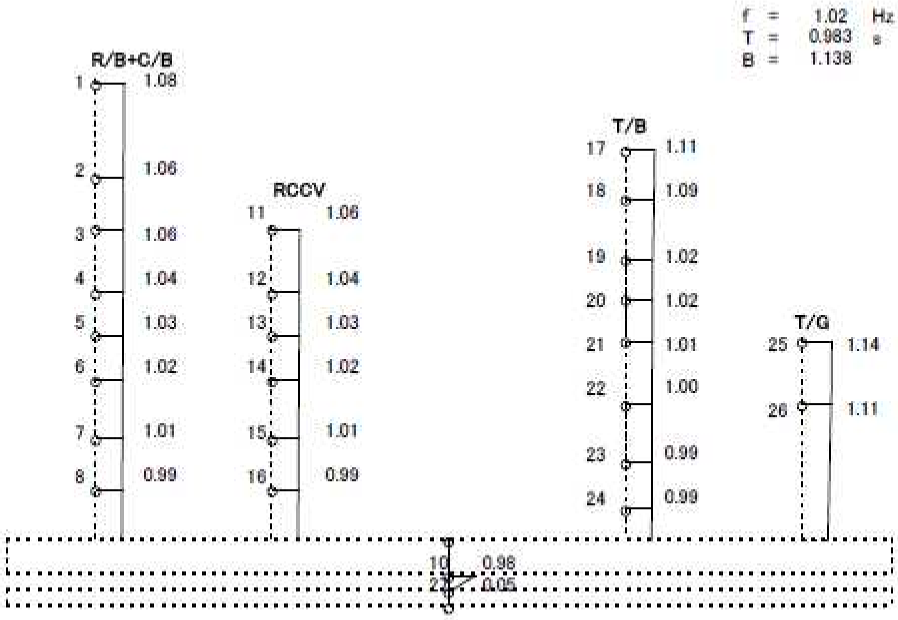
Fig 1-23 Seismic response analysis model of BWR common foundation type seismic isolation building (N-S)

Table 1-16 Analysis model of seismic isolation device (horizontal)

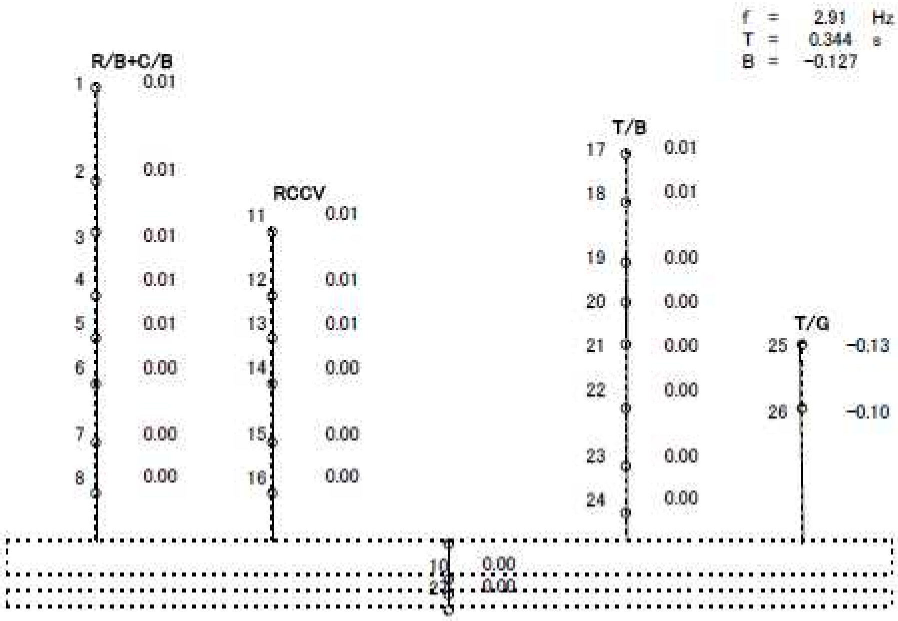
Motion type	Object	Model	Remarks
Horizontal	Laminated rubber bearing	Nonlinear horizontal spring	- The whole seismic isolated layer is represented by a single horizontal spring. - Hardening characteristics is considered in the nonlinear spring
	Lead plug	Nonlinear horizontal spring	- The whole seismic isolated layer i is represented by a single horizontal spring.
Rocking	Laminated rubber bearing	Nonlinear vertical spring	- The whole seismic isolation device story is modeled as a group of multiple vertical springs - The springs are laid out in the horizontal direction, enabling the evaluation of how the axial force acting on the seismic isolation device changes in response to the rocking motion.

b. Eigenvalue analysis

The seismic isolation device (lead rubber bearing) has a nonlinear restoration force characteristic in the horizontal direction. Therefore, the eigenvalue analysis was conducted assuming the primary stiffness before the yielding of lead plug. Figs. 1-24 and 1-25 show the results of eigenvalue analysis. In the horizontal direction, the vibration modes unique to horizontal isolation, associated with the rigid body displacement of the superstructure, are dominant. In the higher order modes, the participation function values of those vibration modes are small.

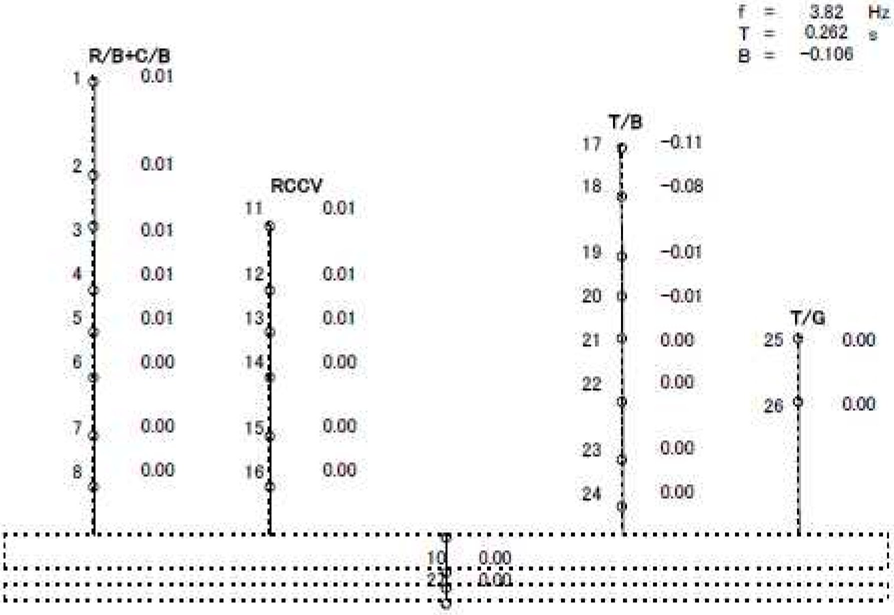


a. 1st modal participation function

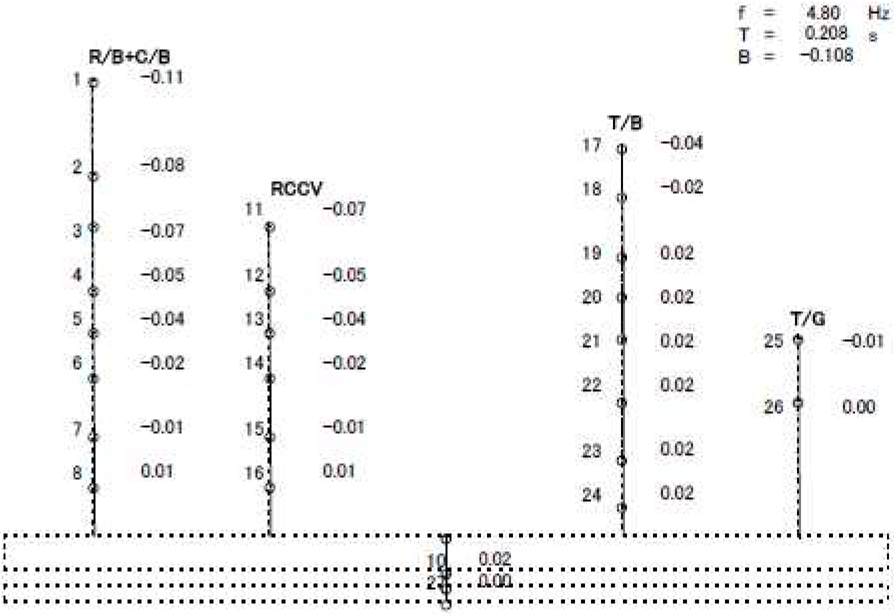


b. 2nd modal participation function

Fig. 1-24 1st and 2nd modal participation functions in the horizontal direction from the eigenvalue analysis



c. 3rd modal participation function



d. 4th modal participation function

Fig. 1-25 3rd and 4th modal participation functions in the horizontal direction from the eigenvalue analysis

(2) Model for the seismic response analysis in the vertical direction

a. Seismic response analysis model

Fig. 1-26 illustrates the vertical seismic response analysis model. Table 1-17 explains the modeling of the seismic isolation device. The response analysis of superstructure is conducted using multiple lumped mass model with axial elastic bar elements which correspond to the estimated axial-stiffness of structures such as shear walls. The reactor building (R/B), the control building (C/B) and the reinforced concrete containment vessel (RCCV) are integrated to a single axial bar model. Turbine building (building T/B and turbine pedestal T/G) is represented by two axial-bar models which are similar to the analysis model in the horizontal direction. The seismic isolated layer is represented by a single axial spring that is assigned the estimated axial rigidity of the whole seismic isolation devices In addition, interactions with the soil are considered using vertical soil spring under lower basemat .

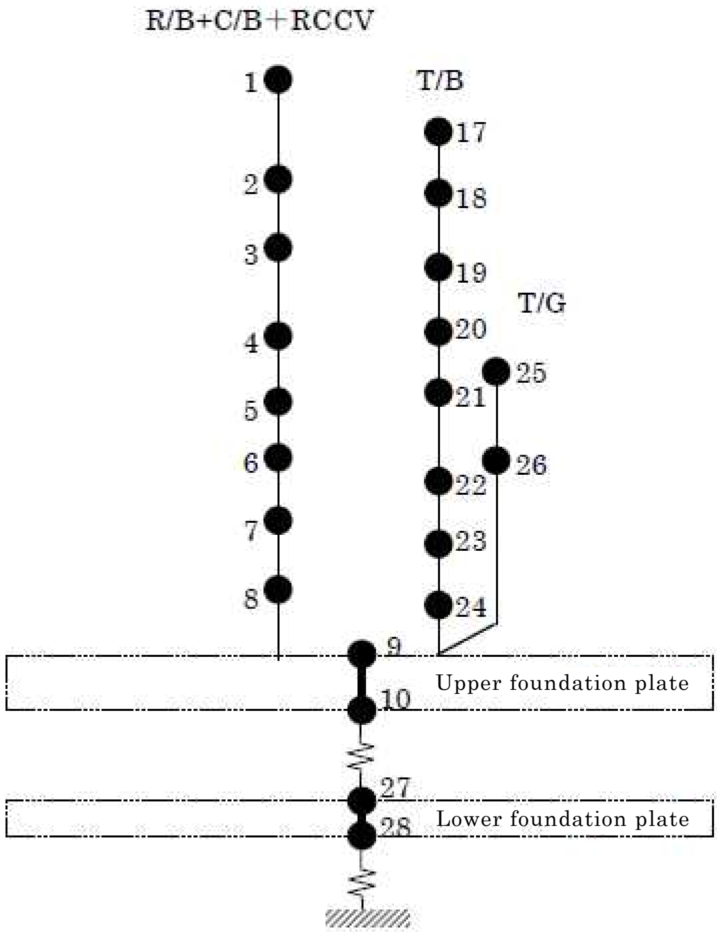


Fig 1-26 Model for the seismic response analysis of BWR common foundation type seismic isolation building in the vertical direction

Table 1-17 Analysis model of seismic isolation device (vertical)

Motion type	Object	Model	Remarks
Vertical	Laminated rubber bearing	Nonlinear vertical spring	- The whole isolated layer is represented by a single spring. - The model is able to evaluate changes of the axial force working on the seismic isolation device .
	Lead plug	Excluded from the scope of modeling	

b. Eigenvalue analysis

The seismic isolation device (lead rubber bearing) has a nonlinear restoration force characteristic in the vertical direction. The axial stiffness of the bearing differs by whether it is in compressive region or tensile region. Therefore, the eigenvalue analysis was conducted considering compressive stiffness . Fig. 1-27 and Fig. 1-28 show the results of eigenvalue analysis:

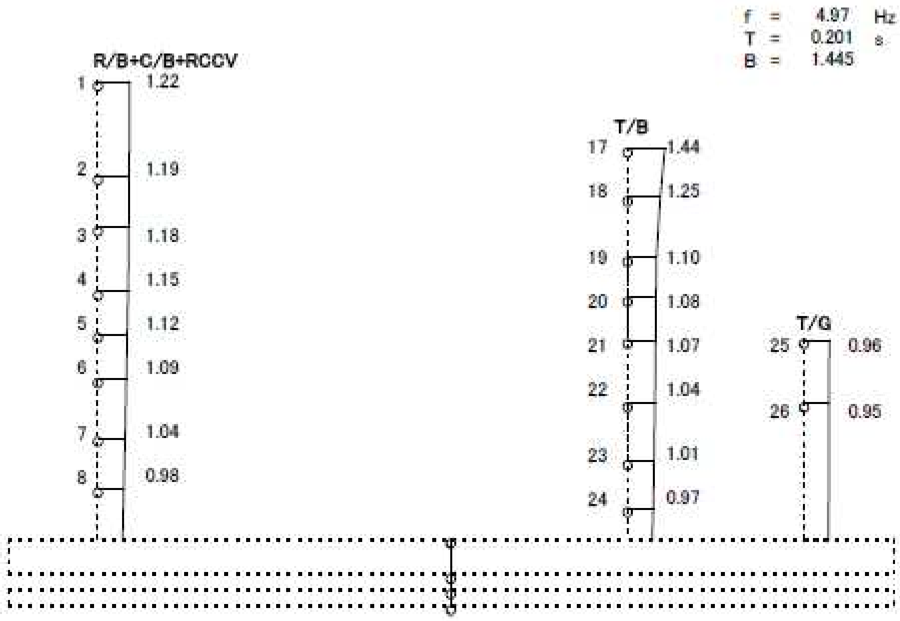
(3) Variations of characteristics of seismic isolation device

In seismic response analysis, variations of horizontal characteristics in the seismic isolation device are considered (variations originating in the manufacturing process, variations caused by aging and the environment temperature). Table 1-18 shows variations of horizontal characteristics as a degree of variability to standard characteristics used in the trial design.

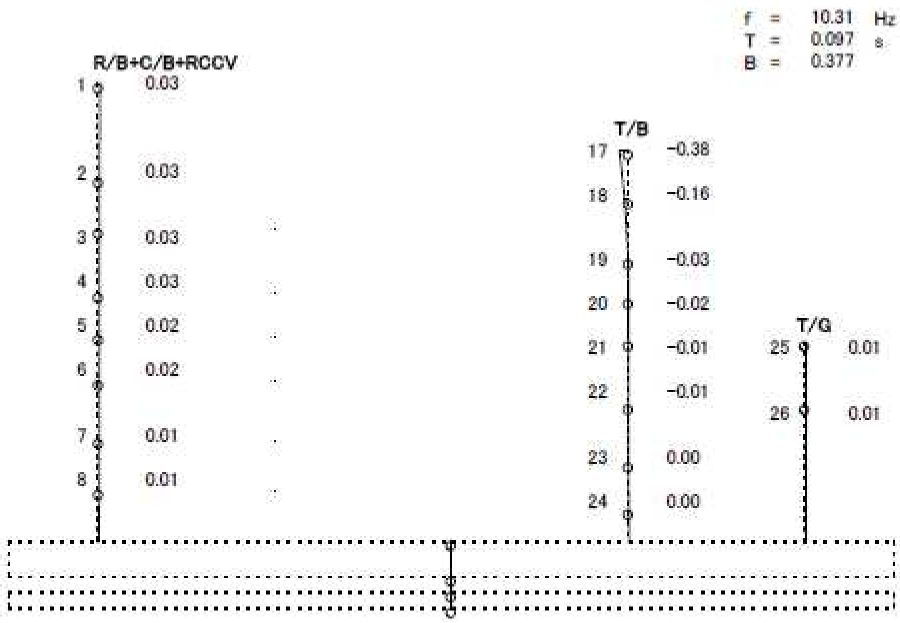
Table 1-18 Variations of characteristics of seismic isolation device

Horizontal direction			
Variation in the negative side		Variation in the positive side	
Rubber stiffness	Yield load of lead	Rubber stiffness	Yield load of lead
-15%	-20%	+35%	+30%

- Negative variation: In case of decreasing stiffness of rubber and yield load of lead caused by variation of products, aging and environment temperature.
- Positive variation: In case of increasing stiffness of rubber and yield load of lead caused by variation of products, aging and environment temperature.

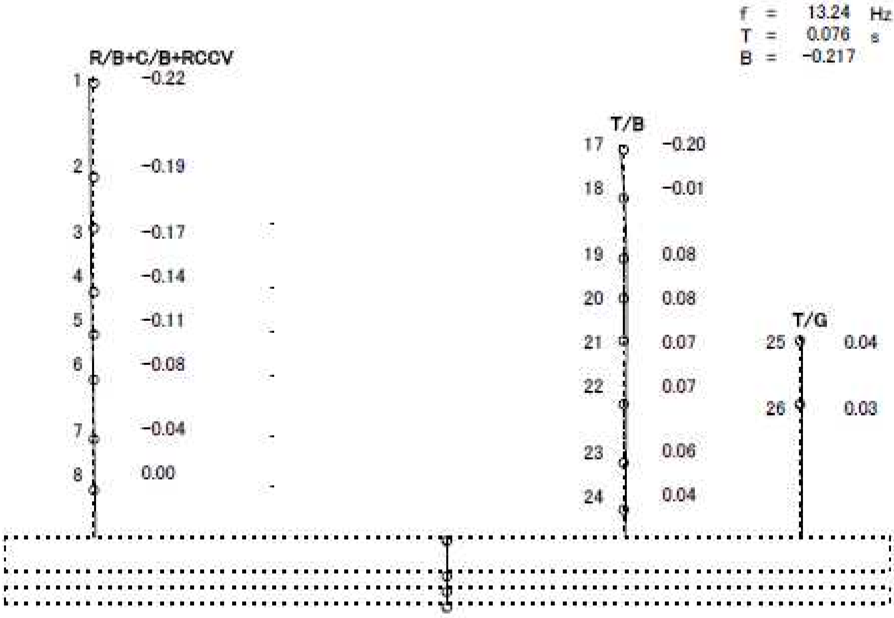


a. 1st modal participation function

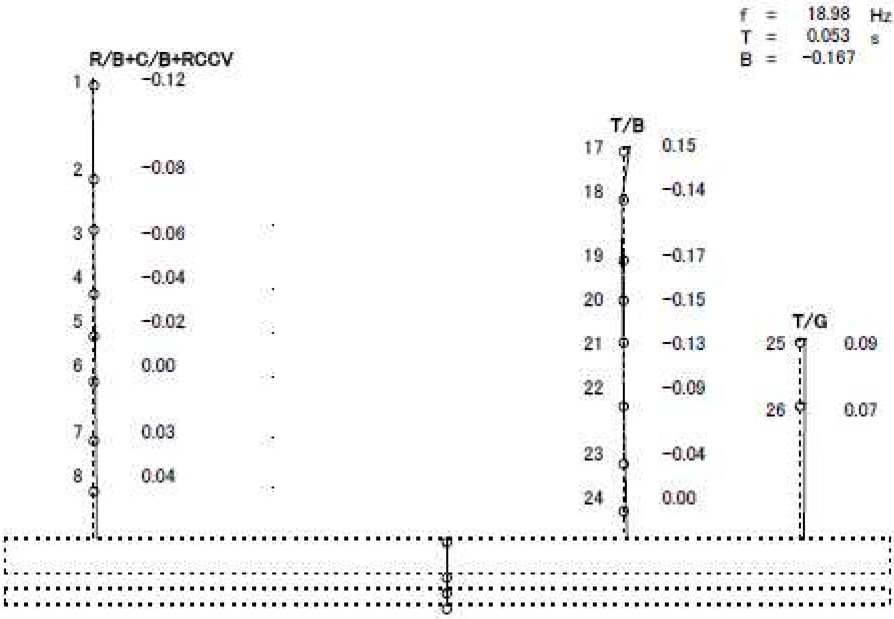


b. 2nd modal participation function

Fig. 1-27 1st and 2nd modal participation functions in the vertical direction from the eigenvalue analysis



c. 3rd modal participation function



d. 4th modal participation function

Fig. 1-28 3rd and 4th modal participation functions in the vertical direction from the eigenvalue analysis

(4) Seismic response analysis results

a. Result of seismic response analysis in the horizontal direction

Figs. 1-29 and 1-30 show the distributions of the maximum response values of acceleration, displacement, shearing stress and shearing strain. The maximum acceleration of the upper basemat is significantly smaller than that of the input ground motion (800cm/sec^2).

Table 1-19 shows the maximum shear strain of the reactor building (with variations in the seismic isolation device characteristics being considered). The maximum response shear strain is much lower than the design target. Therefore it is expected that the stress to each structural element in the reactor building would be smaller than the short-term allowable limit.

Table 1-20 shows maximum response values of seismic isolated layer . Those results meet the target of the seismic isolated layer.

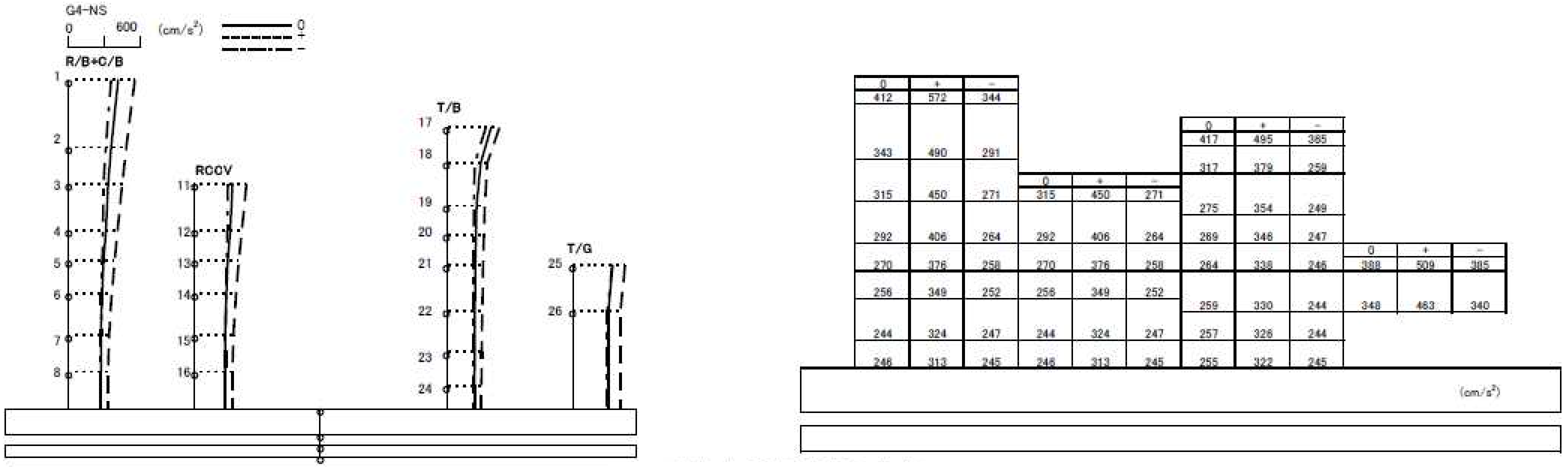
Table 1-19 Maximum shear strain of reactor building

	position of member (between nodes)	Design target*	Response result		
			Standard characteristics	Variation in the positive side	Variation in the negative side
R/B+C/B	Between 7-8	228×10^{-6} or less	109×10^{-6}	154×10^{-6}	103×10^{-6}
RCCV	Between 15-16	241×10^{-6} or less	90×10^{-6}	127×10^{-6}	86×10^{-6}

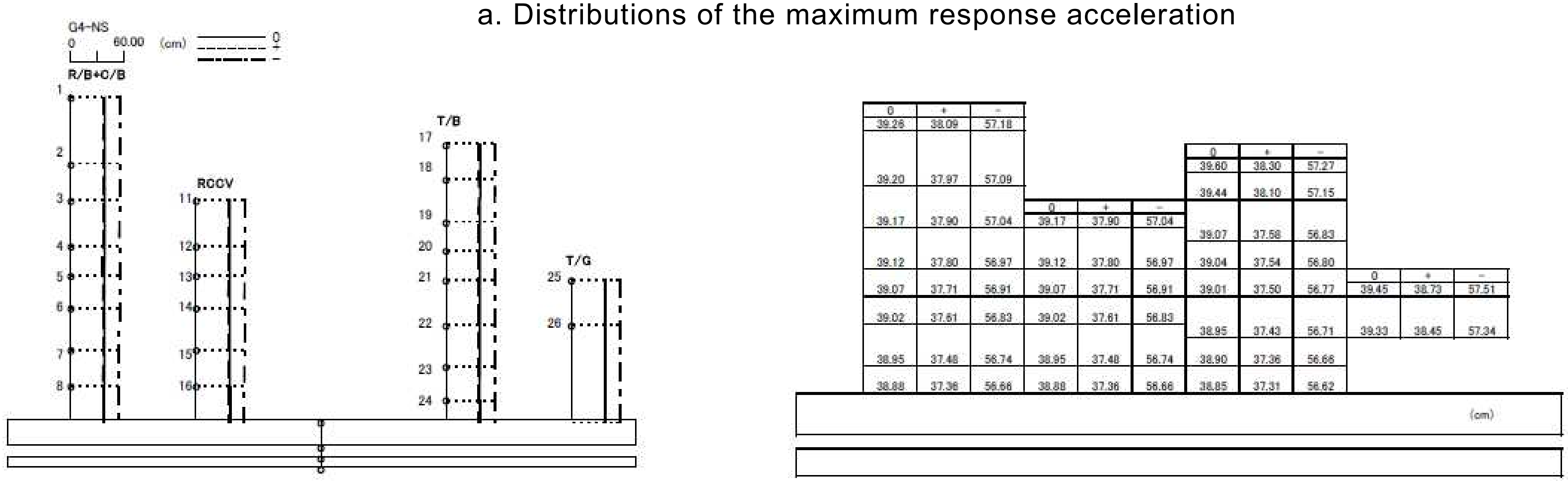
* Within the shear crack point in the restoring force characteristics curve of reinforced concrete shear wall

Table 1-20 Maximum response values of seismic isolated layer

	Design target	Response result		
		Standard characteristics	Variation in the positive side	Variation in the negative side
Maximum relative displacement of the seismic isolated layer (cm)	Approx. 60 or less	38.5	36.9	58.4
Maximum response acceleration of the upper basemat (cm/s^2)	Approx. 300 or less	253	320	245



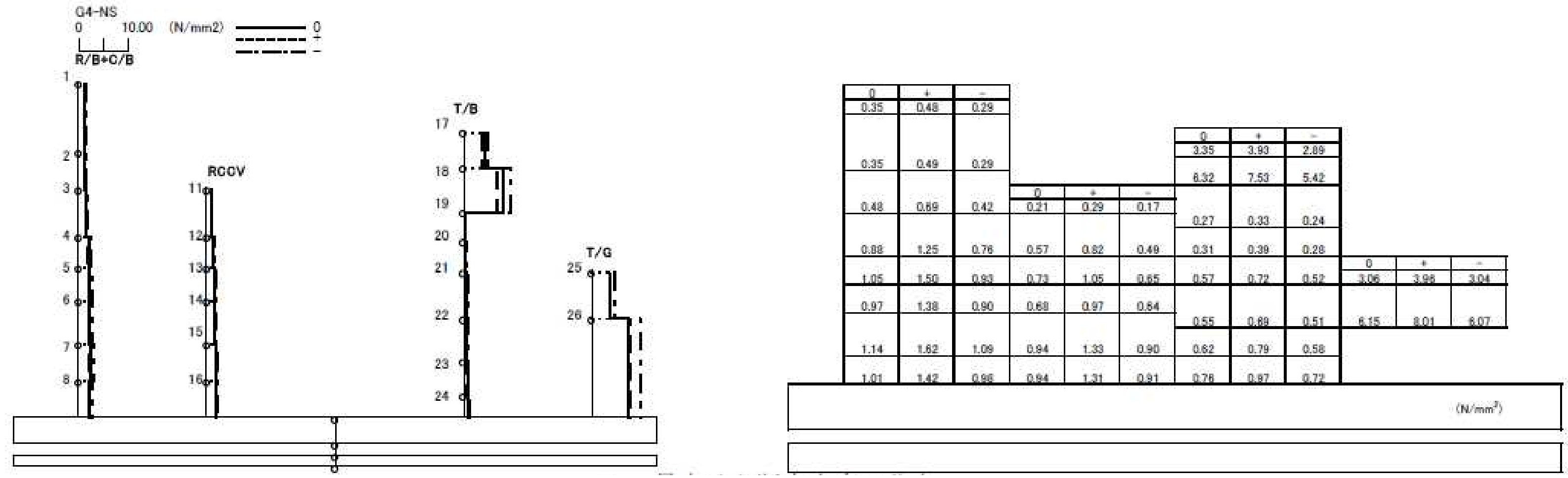
a. Distributions of the maximum response acceleration



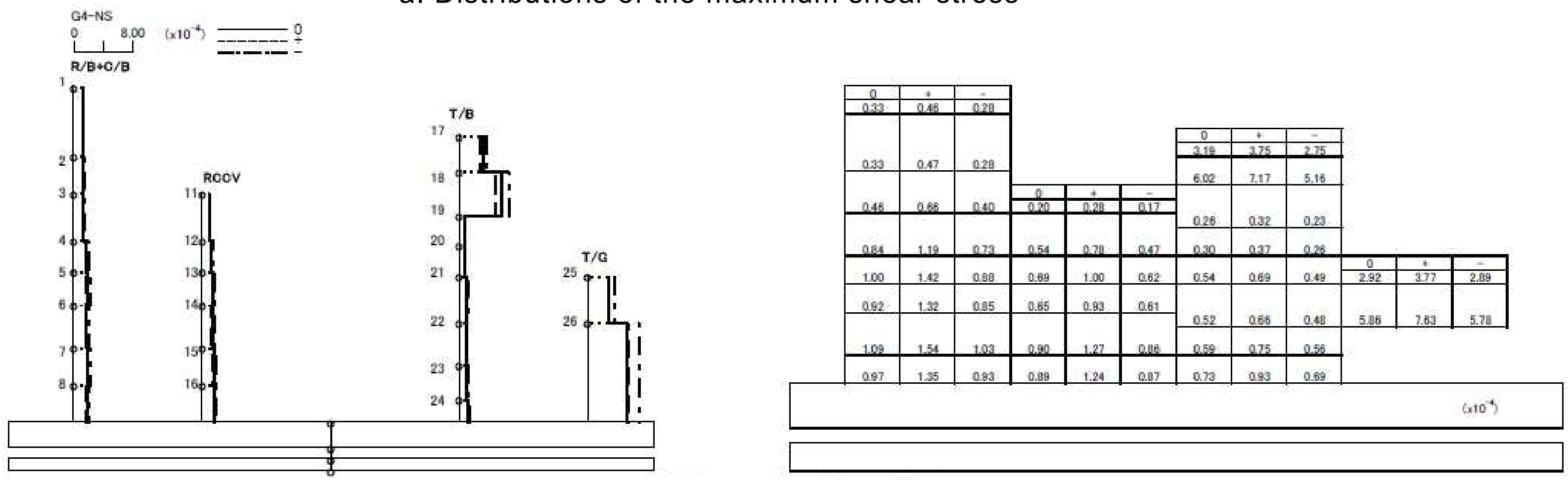
b. Distributions of the maximum response displacement

(Standard characteristics of LRB are represented as 0. Variation in the positive side is represented as +. Variation in the negative side is represented as -.)

Fig. 1-29 Response results of superstructure (maximum acceleration and maximum displacement)



a. Distributions of the maximum shear stress



b. Distributions of the maximum shear strain

(Standard characteristics of LRB are represented as 0. Variation in the positive side is represented as +.
Variation in the negative side is represented as -.)

Fig. 1-30 Response results of superstructure (maximum shear stress and maximum shear strain)

b. Result of seismic response analysis in the vertical direction

Figs. 1-31 and 1-32 show the distributions of the maximum response vertical acceleration and axial force of superstructure. The maximum response vertical acceleration of the upper basemat is slightly higher than the maximum acceleration in the input ground motion (533cm/sec^2).

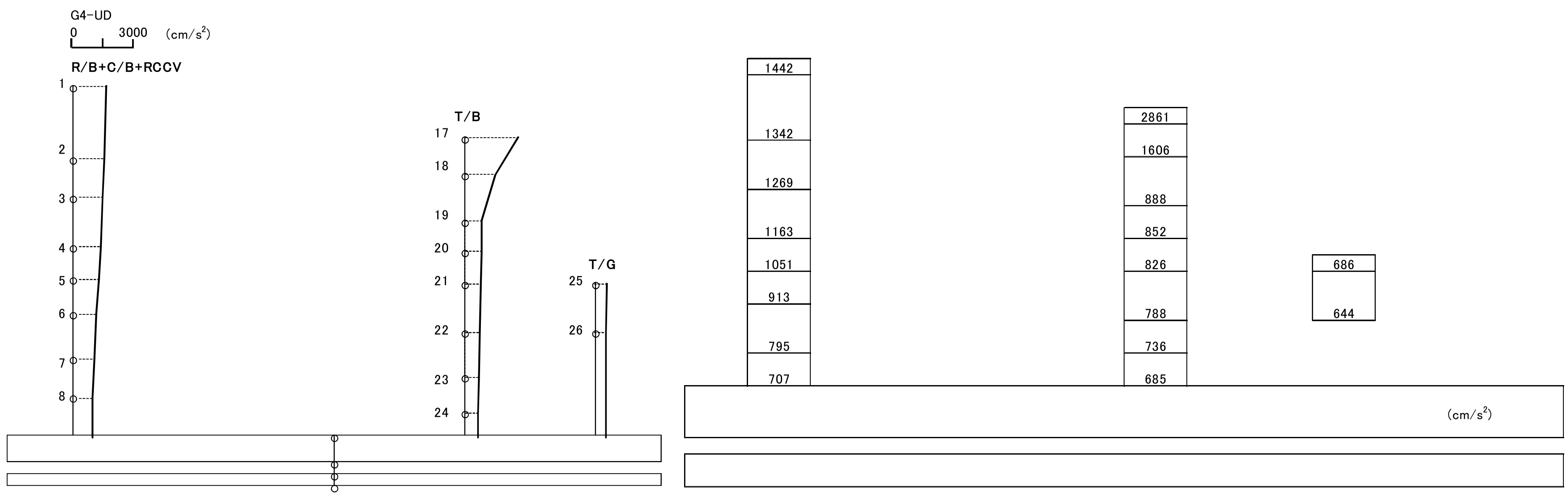


Fig. 1-31 Distributions of the maximum response vertical acceleration of superstructure

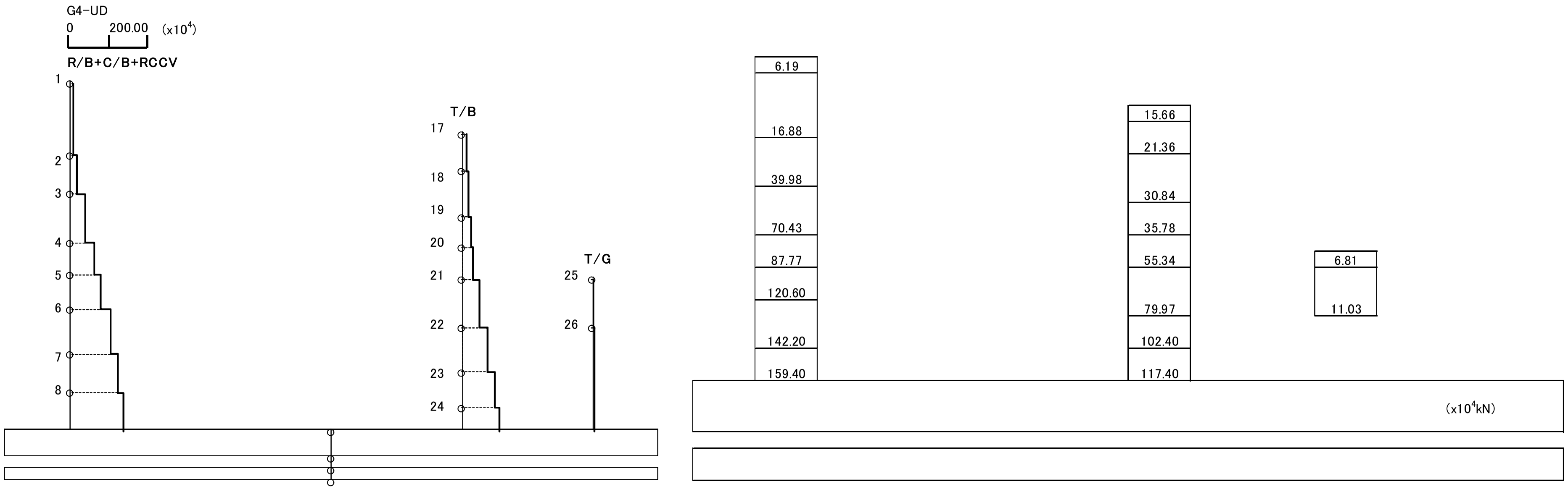


Fig. 1-32 Distributions of the maximum response axial force of superstructure

1.2.7 Verification of design of the seismic isolation device

Table 1-21 reproduces the design targets for seismic isolation device (the lead rubber bearing):

Table 1-21 Design targets of seismic isolation device

Item	Design target	
Shear strain of lead rubber bearing	Standard characteristics	Not exceed 166% (1/1.5 of the linear strain limit)
	Considering variation of characteristics*	Not exceed 250% (the linear strain limit)
Tensile pressure of lead rubber bearing	not exceed 1 N/mm^2	

∗ In case of characteristics variation caused by variations of products, aging and environment temperature.

(1) Maximum shear strain of seismic isolation device

Table 1-22 shows the maximum shear strain on the seismic isolation device due to the design basis ground motion. Assuming the standard characteristics values, the maximum strain of the seismic isolation device is expected to be 148%, which meets the design target of not to allow the strain to go above 166%. Even when the variations of characteristics are considered, the maximum strain is expected to be sufficiently lower than 250% as the design target.

Table 1-22 Maximum shear strain of seismic isolation device

	Response result		
	Standard characteristics	Variation in the positive side	Variation in the negative side
Maximum shear strain (total rubber thickness: 26cm)	148% (38.5cm)*	142% (36.9cm)*	217% (56.4cm)*
Design target	166% or less	250% or less	

∗( ) is represented as maximum relative displacement of seismic isolation device.

(2) Axial pressure of laminated rubber bearing

Table 1-23 shows long-term axial pressure on the seismic isolation device and the fluctuation of the axial pressure on the seismic isolation device in the two cases of: the input solely of the horizontal design basis ground motion and the input solely of the vertical design basis ground motion. Also the table shows the evaluation results of the axial pressures by the absolute value summation method utilizing the results produced by the input solely of the horizontal and vertical design basis ground motion.

The tensile force due to the input ground motion solely of each direction doesn't occur because the axial pressure fluctuation is lower than the long-term axial pressure. The evaluation results of the tensile force by the absolute value summation method shows $0.03N/mm^2$, however, that is found to be lower than $1.0N/mm^2$. The result of evaluation demonstrates compliance with the design target.

Evaluations were conducted by not only absolute value sum method but also SRSS, coefficient combination method and the simultaneous input of the horizontal and vertical ground motion for reference of the evaluation of tensile force.

Table 1-24 shows result of evaluation of tensile force to seismic isolation device.

The seismic response analysis by the simultaneous input of the horizontal and vertical ground motion was conducted using an analysis model based on a model for the response analysis in the horizontal direction, which was modified by adding the characteristics of the superstructure in the axial direction.

The tensile force at the seismic isolation device did not occur in the results of SRSS, coefficient combination method and the simultaneous input of the horizontal and vertical ground motion.

Table 1-23 Result of evaluation of tensile force to seismic isolation device (1)

	Horizontal characteristics of seismic isolation device		
(N/mm^2)	Standard characteristics	Variation in the positive side	Variation in the negative side
Long-term axial pressure	-4.76		
Axial pressure fluctuation by the sole input of the horizontal component of ground motion	0.85	1.13	0.81
Axial pressure fluctuation by the sole input of the vertical component of ground motion	3.66		
Evaluation of tensile force (Absolute value sum method)	-0.25	0.03	-0.29

* A negative value indicates a compressive pressure.

Table 1-24 Result of evaluation of tensile force to seismic isolation device (2)

Axial pressure*(N/mm²)	Horizontal characteristics of seismic isolation device		
	Standard characteristics	Variation in the positive side	Variation in the negative side
Long-term axial pressure	-4.76		
Axial pressure fluctuation by the sole input of the horizontal component of ground motion	0.85	1.13	0.81
Axial pressure fluctuation by the sole input of the vertical component of ground motion	3.66		
Axial pressure fluctuation by the simultaneous input of the horizontal and vertical component of ground motion	4.09	4.09	4.01
Evaluation of tensile force (Absolute value sum method)	-0.25	0.03	-0.29
Evaluation of tensile force (SRSS*)	-1.00	-0.93	-1.01
Evaluation of tensile force (coefficient combination method*)	-0.76	-0.65	-0.77
Evaluation of tensile force (The simultaneous input of the horizontal and vertical component)	-0.67	-0.67	-0.75

∗ A negative value indicates a compressive pressure.

∗ SRSS: $\sigma = \sigma_L \pm \sqrt{|\sigma_H|^2_{\max} + |\sigma_v|^2_{\max}}$

∗ Coefficient combination method:

$$\sigma = \sigma_L \pm Max\left[1.0|\sigma_H|_{\max} + 0.4|\sigma_v|_{\max}, 0.4|\sigma_H|_{\max} + 1.0|\sigma_v|_{\max}\right]$$

σ_L: Long-term contact pressure

σ_H: Contact pressure fluctuation by the horizontal ground motion

σ_v: Contact pressure fluctuation by the vertical ground motion

1.2.8 Conclusion

The trial design of BWR common foundation type seismic isolation building characterized by the placement of the reactor building, the control building and the turbine building on the same seismic isolated basemat was carried out. The results of seismic response analysis, conducted using the design basis ground motion as the input, demonstrated conformity with the design target values.

1.3 Development of Seismic Isolated Light-water Reactor Plant in the Next-generation

(Summary for the papers submitted to the Architectural Institute of Japan, Sep. 2010)

1.3.1 Introduction

The Ministry of Economy, Trade and Industry (METI), the Federation of Electric Power Companies (FEPC), and the Japan Electrical Manufacturers' Association (JEMA) announced in September 2007 that they would undertake a project to develop next-generation light water reactors. The governmental and private sector development project started in April 2008, with the Institute of Applied Energy being a core organization and the participation of domestic reactor manufactures Mitsubishi Heavy Industries, Hitachi-GE and Toshiba Corporation.

The next-generation light water reactors are planned for commercialization in around 2030. They will be plants based on international standards and will be in base-isolated buildings that can withstand earthquakes regardless of seismic intensity. Fig.1 and 2 show the schematic overviews of next-generation PWR and BWR, respectively.

A number of papers on the development of base isolation technologies submitted to the Architectural Institute of Japan presented the outcome of the development of base isolation technologies for the next-generation light water reactor buildings.

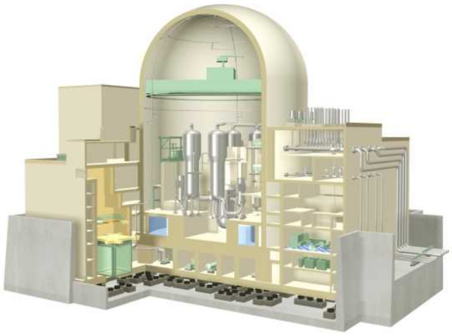


Fig. 1 Schematic overview of next-generation PWR

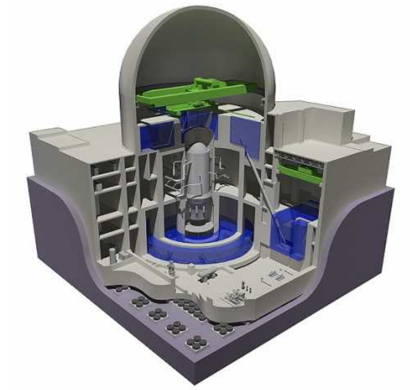


Fig. 2 Schematic overview of next-generation BWR

1.3.2 Outcome of development of base isolation technologies

1.3.2.1 Base isolator design conditions

(1) Studied earthquake ground motions

The following two types of earthquake ground motions, as plotted in Fig.3, were investigated.

- Standard ground motion that broadly envelopes Ss ground motions observed in Japan (800 gal, 200 kine)
- Site-specific ground motions that exceed the standard ground motion in intensity in a long-period range (site-A and site-B ground motions)

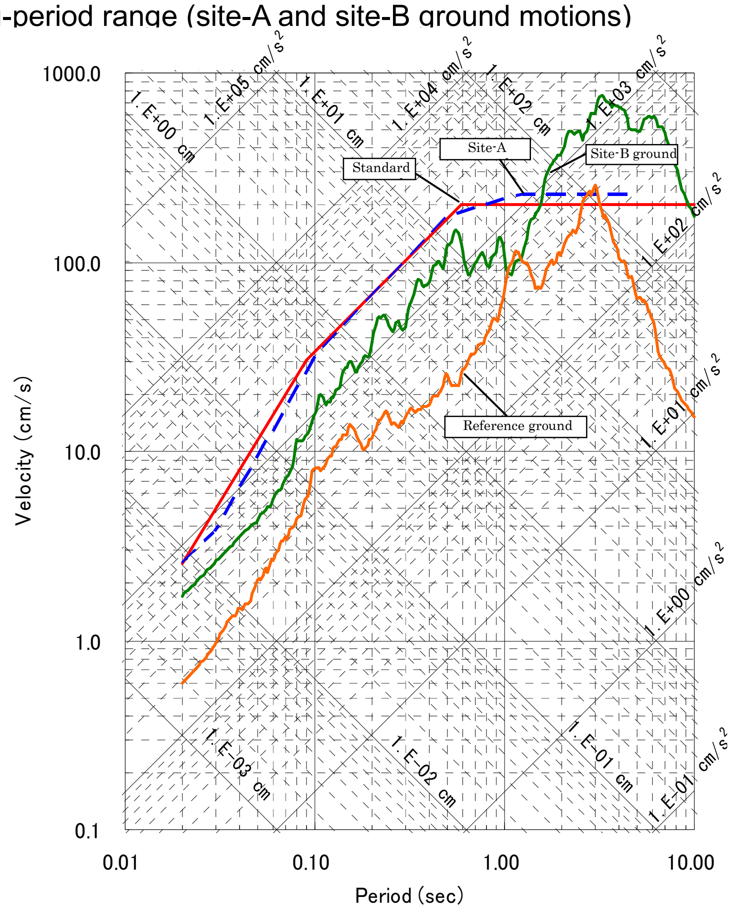


Fig. 3 Comparison of two domestic site-specific ground motions with the studied standard ground motion

(2) Studied base isolator conditions

Lead-plug rubber bearings with a diameter of 1600 mm were adopted for the base isolator; this is the maximum size available among the Japanese base isolator manufactures. Two types of rubber, G4 and G6, were selected.

Table 1 shows the basic properties of the base isolator determined in view of the equipment requirements, and Table 2 shows the reference responses of the base isolator.

Table 1 Basic properties of base isolator

Rubber diameter	Maximum diameter (□□1600 mm) available in the industry
Rubber type	G4 rubber, G6 rubber
First period, T1	G4 rubber: $T1=T2/\sqrt{(K_1/K_H)}$ *, G6 rubber: $T1=T2/\sqrt{(K_1/K_H)}$ *,
Base isolation period, T2	0.2 to 0.4 sec < T2 < 4.0 to 5.0 sec
Yield earthquake intensity, β	0.05 or more
Vertical frequency	Vertical frequency: approx. 10 to 20 Hz

* K_1/K_H: first to second rigidity ratio of base isolation

Table 2 Reference responses of base isolator

Relative displacement between buildings	40 cm or less
Building response acceleration	300 gal or less
Design limit	1/1.5 of linear finite strain

1.3.2.2 Results of seismic response analysis of base-isolated buildings

(1) PWR reactor building

A reactor building was rendered into a multi-mass beam model, with a sway-rocking response analysis model (S/R model) applied to horizontal ground motions and a vertical response analysis model applied to vertical ground motions. Ground springs were assumed in both cases. In the base isolator, one shear spring and multiple axial springs were arranged for the horizontal direction, and one axial spring was arranged for the vertical direction. Fig. 4 shows the specifications of the base isolator, and Fig. 5 a seismic response analysis model for the horizontal direction.

Fig.6 shows seismic response analysis results for the upper building structure and the base isolator. Their marginal performance was investigated by applying multiplication factors to three standard ground motions with different phases. As a result, it was found that the base isolator would fail in advance of the upper building structure at 2 to 2.5 times the intensity of the standard ground motion.

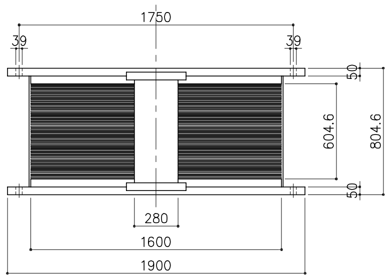
<table>
<tr><td>Equipment diagram (G4)</td><td>
</td></tr>
<tr><td>Equipment specifications</td><td>Rubber diameter:□□□ 1600 mm
Sustained load: 650 tons
Horizontal period T2: 3.2 sec
Yield earthquake intensity β: 0.11
Vertical frequency: 20.4 Hz</td><td>Rubber layer: 5.51 mm × 58 layers
Lead plug diameter: 280 mm
Primary shape factor S1: 72.6
Secondary shape factor S2: 5.01
Lead plug aspect ratio: 2.16</td></tr>
</table>

Fig. 4 Outcome of base isolator design (PWR, G4 rubber)

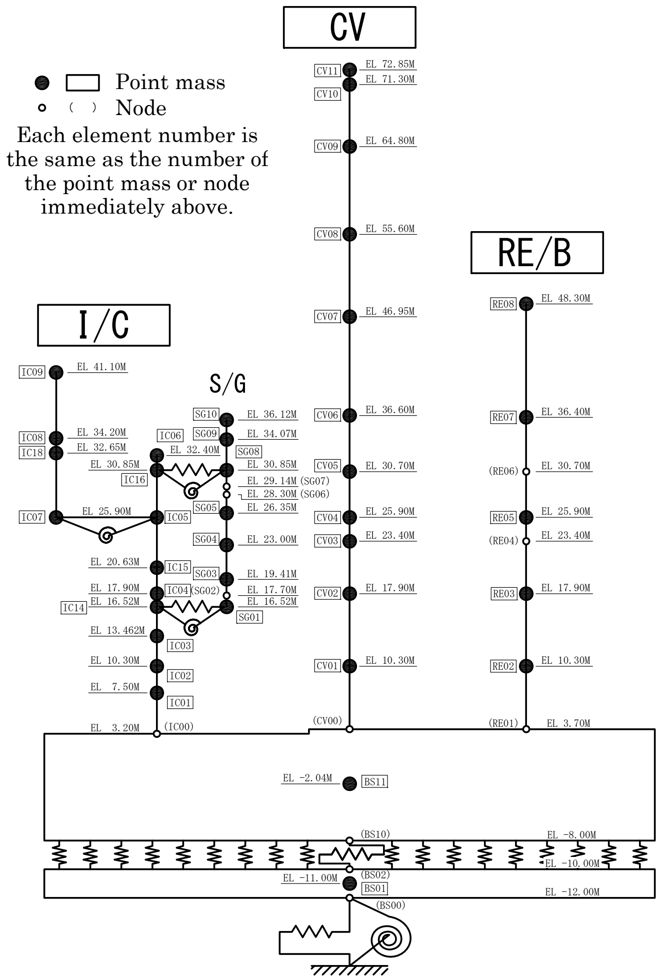
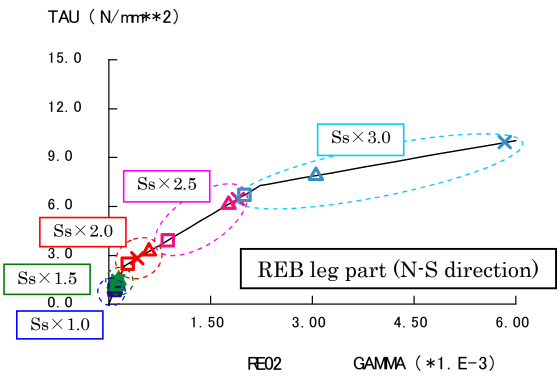


Fig. 5 PWR seismic response analysis model (horizontal direction)



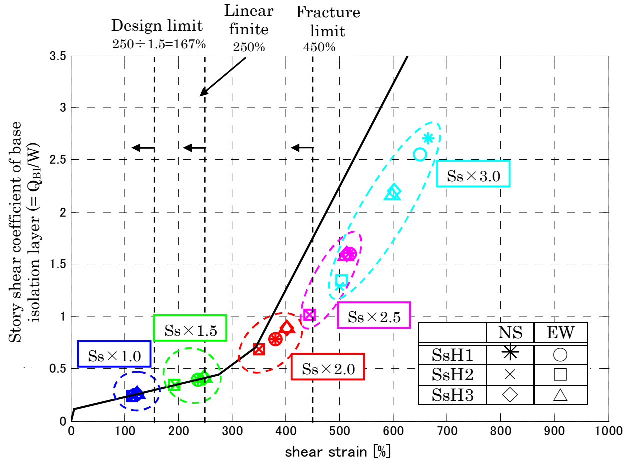


Fig. 6 Result of PWR marginal performance investigation
(left: upper building structure response, right: base isolator response)

(3) BWR reactor building

A seismic response analysis was performed on a BWR reactor building in the same manner as the PWR analysis. The results obtained were similar to those of the PWR case.

Fig 7 shows the specifications of the base isolator, and Fig. 8 a seismic response analysis model for the horizontal direction. Fig. 9 shows the result of seismic response analysis performed on the upper building structure and the base isolator.

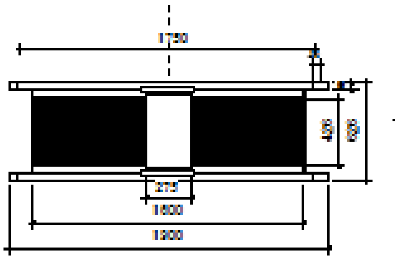
Equipment diagram (G4)		
Equipment specifications	Rubber diameter: 1600 mm Sustained load: 550 tons Horizontal period T2: 2.8 sec Yield earthquake intensity β: 0.1 Vertical frequency: 20.96 Hz	Rubber layer: 10.0 mm × 27 layers Lead plug diameter: 275 mm Primary shape factor S1: 40.0 Secondary shape factor S2: 5.93 Lead plug aspect ratio: 1.62

Fig. 7 Outcome of base isolator design
(base isolation of BWR reactor building only, G4 rubber)

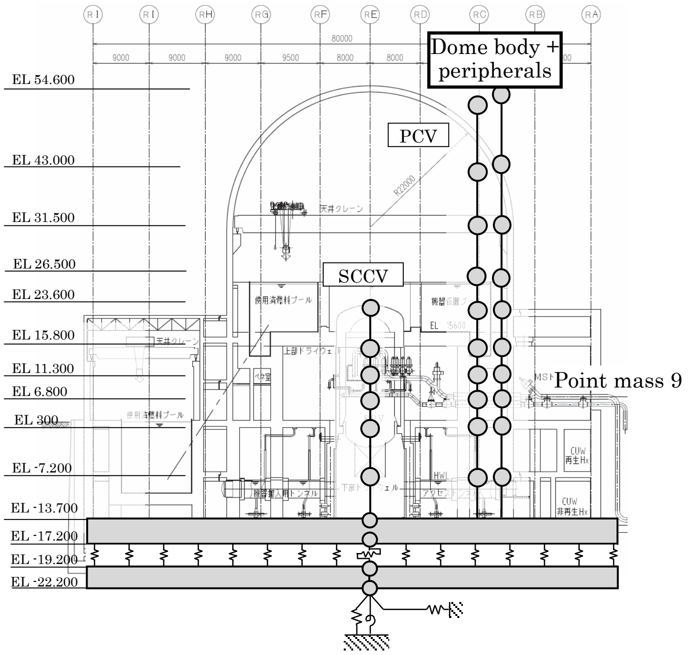


Fig. 8 The analysis model for the base isolation of BWR reactor building only

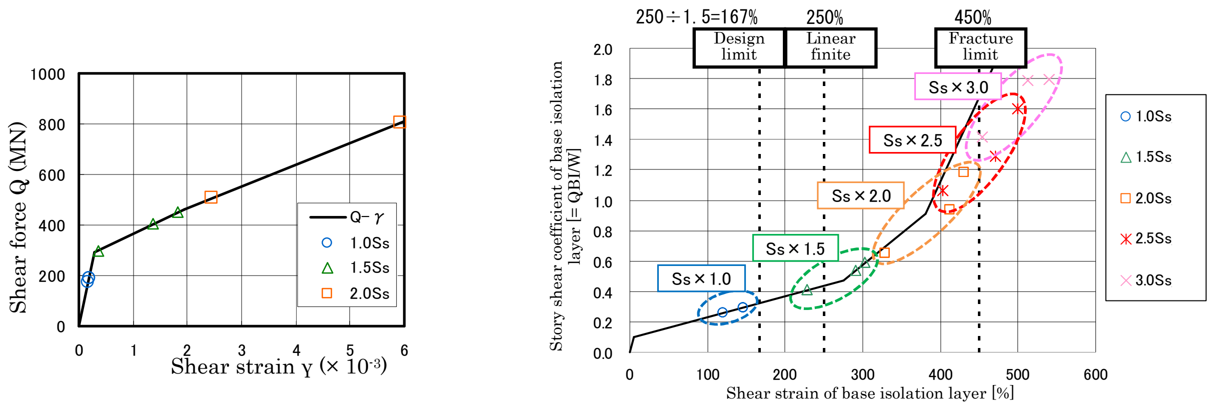


Fig. 9 Result of BWR marginal performance investigation
(left: upper building structure response, right: base isolator response)

(4) BWR reactor building and turbine building (base isolation of common foundation)

In the same manner as the PWR analysis, a seismic response analysis was performed on a common foundation for a BWR reactor building and a turbine building with a base isolator installed on the common foundation. The results obtained were similar to those of the PWR case.

Fig.10 shows the specifications of the base isolator, and Fig.11 a seismic response analysis model for the horizontal direction. Fig.12 shows the result of seismic response analysis performed on the upper building structure and the base isolator.

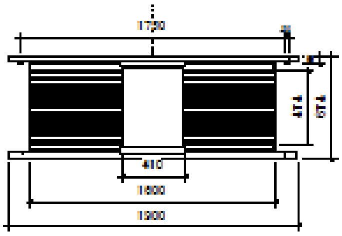
<table>
<tr><td>Equipment diagram (G4)</td><td>
</td></tr>
<tr><td>Equipment specifications</td><td>Rubber diameter:□□□ 1600 mm
Sustained load: 1000 tons
Horizontal period T2: 3.5 sec
Yield earthquake intensity β: 0.12
Vertical frequency: 18.59 Hz</td><td>Rubber layer: 6 mm × 40 layers
Lead plug diameter: 410 mm
Primary shape factor S1: 66.67
Secondary shape factor S2: 6.67
Lead plug aspect ratio: 1.20</td></tr>
</table>

Fig. 10 Outcome of base isolator design
(base isolation of BWR common foundation, G4 rubber)

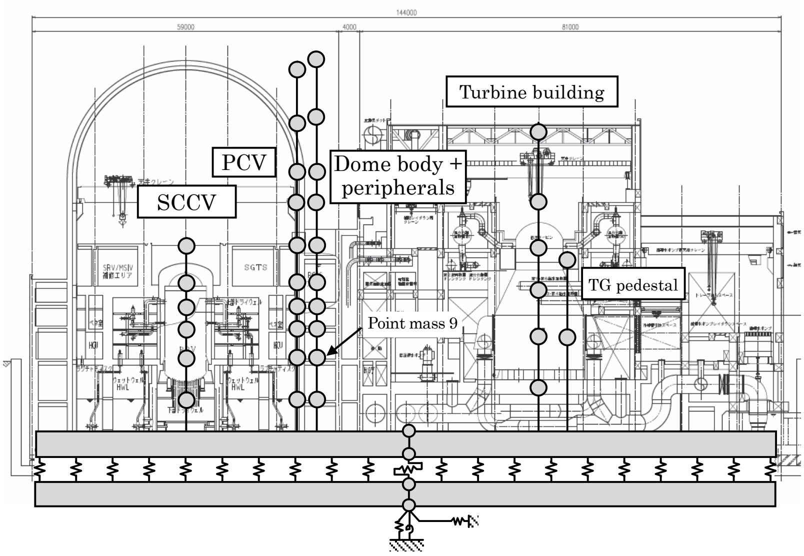


Fig. 11 Tthe analysis model for a base-isolated building with a common BWR foundation

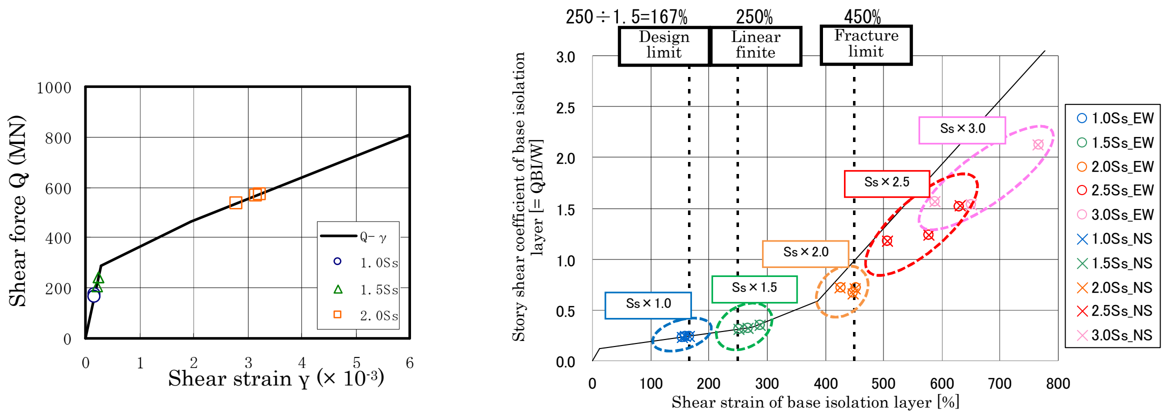
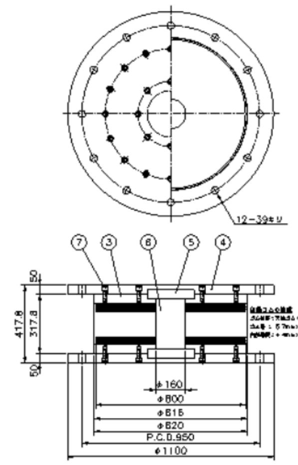


Fig. 12 Result of BWR marginal performance investigation
(left: upper building structure response, right: base isolator response)

1.3.2.3 Basic tensile fracture test on large base isolator

To investigate the basic properties of the base isolator, a tensile fracture test was conducted within the range that can be tested with the existing equipment. Fig.13 shows the base isolator used for the test, the bearing diameter of which is half the actual diameter.

Table 3 shows the stress application program of the test and the fracture strain observed during the test. The fracture strain observed when the base isolator was subjected to a surface pressure (from No. 2 to No. 12) mostly exceeded 450%, and the test sample failed as the laminated rubber underwent shear movement. As an example of the tensile test result, Fig.14 shows the relationship between load and displacement when the test sample was subjected to an axial stress of 5 MPa.



External diameter = 800 mm

Lead diameter = 160 mm

Rubber thickness = 5.7 mm

Number of rubber layers = 22

Primary shape factor = 35.1

Secondary shape factor = 6.4

Fig. 13 Example of test sample (base isolator)

Table 3 Basic properties measured in different stress application programs

Stress application program number	Test conditions		Test sample	Fracture strain (%)	Fracture load (kN)	Vertical displacement at the time of fracture (mm)	Linear finite strain (%)	
	Axial stress	Horizontal stress					at the time of 400% first loading	at the time of fracture loading
1	2.0MPa	Progressive	LRB	−378	−1,397	100*	337	266
2	1.0MPa	Progressive	LRB	486	2,077	7.9	288	339
3	−0.5MPa	Progressive	LRB	526	2,730	- 2.5	284	337
4	−5.0MPa	Progressive	LRB	520	2,386	- 8.6	284	340
5	−5.0MPa	Progressive	LRB	511	2,229	- 5.5	293	341
6	−5.0MPa	Progressive	LRB	526	2,970	- 5.2	279	328
7	−5.0MPa	Monotonous	LRB	463	2,161	- 3.7		278
8	−10.0MPa	Progressive	LRB	490	2,006	- 8.3	292	340
9	2.0MPa	Monotonous	LRB	442	2,286	10.3		282
10	−30MPa	Progressive	LRB	531	1,916	- 30.6	306	368
11	−5.0MPa	Progressive	RB	514	2,912	- 7.2	368	333
12	−5.0MPa	Monotonous	RB	450	2,395	- 5.8		287

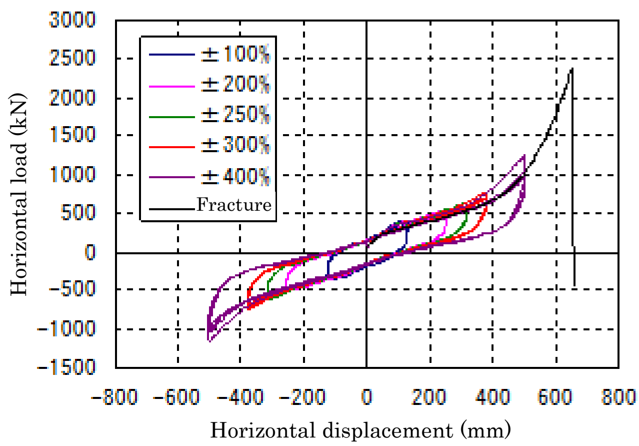


Fig. 14 Load-displacement relationship during progressive loading
(Load program #4)

1.3.2.4 Basic ultimate stress application test for full-scale base isolator

Using a sample of laminated natural rubber that had been installed on the foundation of a tower crane, a free vibration test and an ultimate stress application test were conducted to investigate the damping performance, fracture mode and load-displacement relationship of the sample. The test equipment arrangement and specimen specifications are shown in Fig. 15 and Table 3, respectively. In the free vibration test, forced displacement was introduced to achieve a 100% shear strain by using a quick release jack and then free vibration was introduced by releasing the jack. In the ultimate stress application test, an 800 ton jack was installed instead of the quick release jack to apply static stress application until the base isolator broke.

Table 3 Specifications of specimen

Upper foundation	Mass	Approx. 2250 tons
	Dimensions	12m×12m×6.5m
Laminated natural rubber	Rubber material	Natural rubber-based (G = 0.39 N/mm^2)
	Rubber diameter	Φ1000mm
	Total rubber thickness	6mm×34＝204mm
	Shape factor	S_1 : 39.6, S_2 : 4.90
	Horizontal stiffness	1485 kN/m (at 100% shear strain)
Steel rod damper (U-shaped damper)	Yield load	112 kN per unit
	Stiffness	5920 kN/n (primary), 100 kN/m
Lead damper	Yield load	90 kN per unit
	Stiffness	12,000 kN/m (primary), 0 kN/m

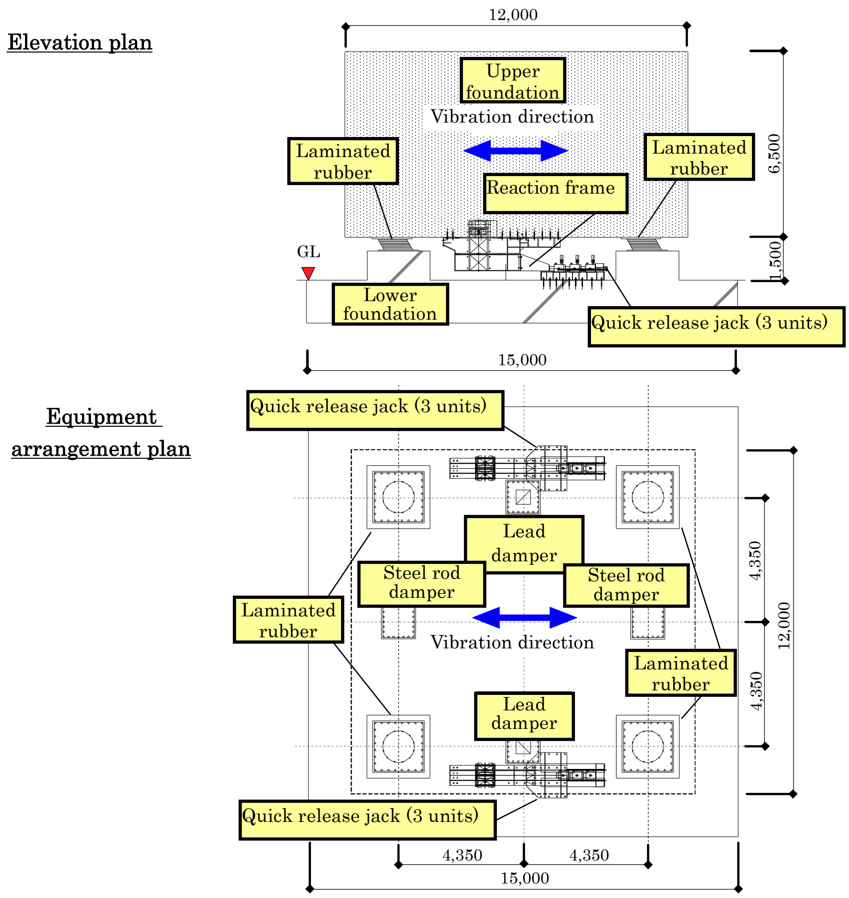


Fig. 15 Test sample elevation plan and equipment arrangement plan

(1) Free vibration test

The equivalent viscous damping factor (Heq) was calculated from a hysteresis loop, and a value of about 20% was found as damping performance. This is an adequate damping factor for a design stage.

(2) Ultimate stress application test

Figure 16 shows the result of the ultimate stress application test.

The linear finite strain is approximately 273%, and the fracture strain is approximately 318%. The obtained linear finite strain is comparative with the previous findings. It is considered, however, that the observed fracture strain reflects a rubber-specific factor.

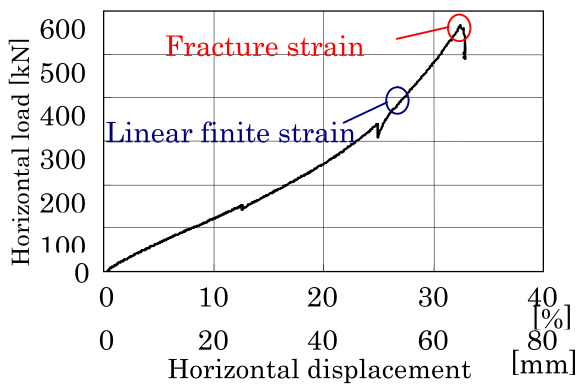


Fig. 16 Relationship between horizontal load and horizontal displacement

1.3.3 References

This paper is a summary of the following papers submitted to the Architectural Institute of Japan (Annual Meeting held in Hokuriku in September 2010).

1) Tomofumi Yamamoto, et al., Development of seismic isolated light-water reactor plant in next-generation (Part 1) Development program of seismic isolation system

2) Hiroshi Shimizu, et al., Development of seismic isolated light-water reactor plant in next-generation (Part 2) Design conditions of seismic isolation system

3) Kunihiko Sato, et al., Development of seismic isolated light-water reactor plant in next-generation (Part 4) Seismic response analysis for the PWR plant

4) Shinji Kosugi, et al., Development of seismic isolated light-water reactor plant in next-generation (Part 5) Seismic response analysis for the BWR plant: Isolated reactor buildings

5) Shinji Asakura, et al., Development of seismic isolated light-water reactor plant in next-generation (Part 6) Seismic response analysis for the BWR plant: common base-mat isolated buildings

6) Masakazu Jinbo, et al., Development of seismic isolated light-water reactor plant in next-generation (Part 7) Large scale test of seismic isolation device

7) Tetsuo Imaoka, et al. Development of seismic isolated light-water reactor plant in next-generation (Part 8) Free vibration test and static test for full-scale base isolation system

2. Examples of Equipment Isolation

2.1 Seismic Reliability Proving Test on Base-Isolated Computer System

2.1.1 Introduction

The proving test consisted in the vibration testing of the full-scale model of a computer system on a seismic isolated floor using a large high-performance shaking table. The purpose of this test was to prove seismic safety and reliability of a computer system placed on seismic isolated floor by vibration test which simulated real seismic condition. In addition, the test was conducted to confirm the validity of the design practices concerning the combination of a computer system and a base-isolated floor system.

Objectives:

(1) Demonstration of the structural integrity, functional maintenance and seismic safety margin of the computer system placed on a seismic isolated floor

(2) Verification of seismic design practices concerning the combination of a computer system with a seismic isolated floor

2.1.2 Test specimens

The test specimens were designed according to the modeling policies described below to ensure that it properly reproduced the structure and functional features of a computer system actually in use. Table 2.1 describes the scope of modeling.

Table 2-1 Scope of computer system modeling (comparison with the real system)

Scope of modeling \ Feature		Dimension / geometry	Weight	Material	Equipment	Function	Remark
Equipment	Computer	○	○	○	○	○	
	Peripheral devices	○	○	○	○	○	
Enclosures	Enclosure casings on the rack	○	○	○	○	–	
	Central operating display panel	△	△	△	△	–	Excluded from the scope of proving test.
	Operator control panel	○	○	○	○	–	
Seismic isolated floor		○	○	○	○	○	Future application to actual plant is presumed.
Description		○ : Fully reproduced △ : Partially reproduced × : Not reproduced – : Outside the scope					

(1) Computer system

1) At nuclear power plants, computer systems are used for various purposes related to plant operation monitoring such as plant status display, plant condition monitoring,

plant performance calculation, core performance calculation, core performance evaluation and automated control. (See Fig. 2-1.) The computer system for the test was chosen as an appropriate computer system used at a typical 1100MWe-class nuclear power plant in Japan.

2) Since the proving test aims to demonstrate not only the rigidity of construction of the computer system but also the functional integrity of the entire system, the test specimen should be made full-scale (1:1) as perfectly as possible, reproducing the configuration of a real computer system at a nuclear power plant.

3) A real computer system at a nuclear power plant is often a complex system having multiple sets of same devices connected in parallel (i.e. more than one CPUs, magnetic disk units, process I/O devices, CRT display units, printers, etc.). In the test specimen, however, the numbers of similar devices should be reduced to minimum that is required to maintain the function.

4) In terms of geometry, configuration, material, installation, etc., the test specimen should be made as identical as possible to a real system.

5) The following criteria should be considered in the selection of test specimens:

(i) Test specimens should be equivalent to those used at nuclear power plants under construction.

(ii) Test specimens should be of the latest models (equivalent those used at nuclear power plants under construction) considering possible replacement, etc.

(iii) Test specimens should include all the devices required to emulate the performance of a real system.

(iv) Considering that the computer systems at different nuclear power plants are similar to each another in terms of structure and operating principle, with no significant difference in terms of seismic resistance too, the test specimens should be most representative one among these systems.

(v) In addition to the typical equipment model mentioned above, test specimen should include devices found desirable to be tested.
(hereinafter referred to as “additionally chosen model.”)

6) Auxiliary equipment, including the power supply system, signal generator and HVAC system, should be placed outside the shaking table, and the test specimen should reproduce operating conditions of real computer system as perfectly as possible.

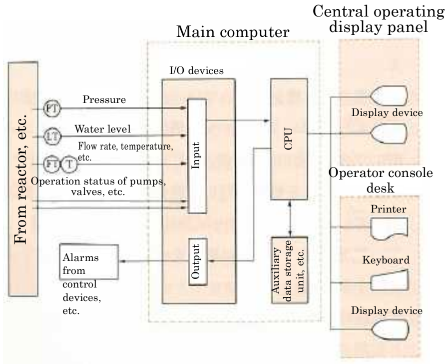


Fig. 2-1 Computer system configuration

(2) Seismic isolated floor

1) Test specimen should have geometry and structure as identical with actual plant as possible.
2) Test specimen should basically be a full-scale (1:1) model.
3) Test specimen should be furnished with as much components as possible that will be required when seismic isolated floor is actually applied in a nuclear power plant.
4) Test specimen should be of one kind and be selected considering the followings:
   (i) Test specimen should satisfy the performance requirements imposed by the computer system.
   (ii) Test specimen should be of the design (function and operating principle) chosen by relatively many manufacturers.
   (iii) Test specimen should support the verification of seismic design practices concerning the computer system used in combination with it.

Fig. 2-2 gives an overview of the test specimen. Fig. 2-3 shows the configuration of the computer system in the test specimens. Table 2-2 lists the specifications of main devices. Table 2-3 lists the specifications of enclosures. The seismic isolated floor specifications are included in Table 2-2 mentioned above. The construction of the seismic isolated floor system is shown in Fig. 2-4.

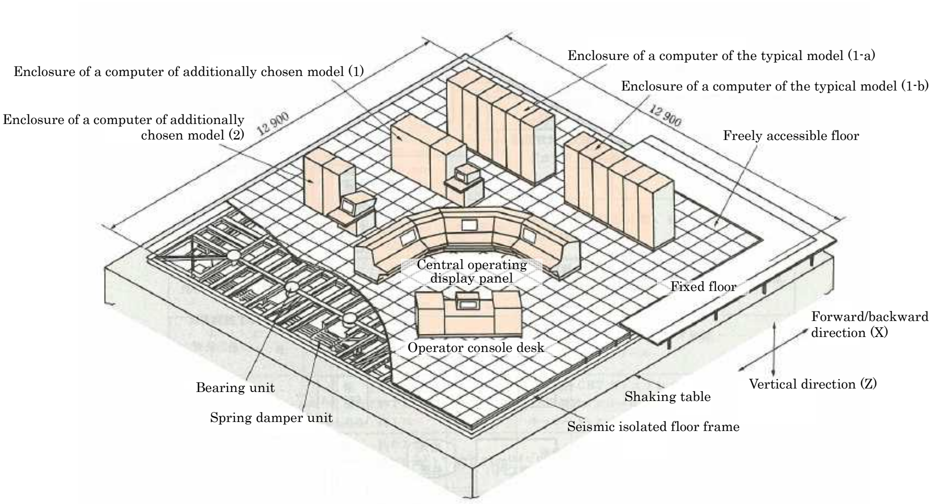


Fig. 2-2 Overview of the computer system test specimen

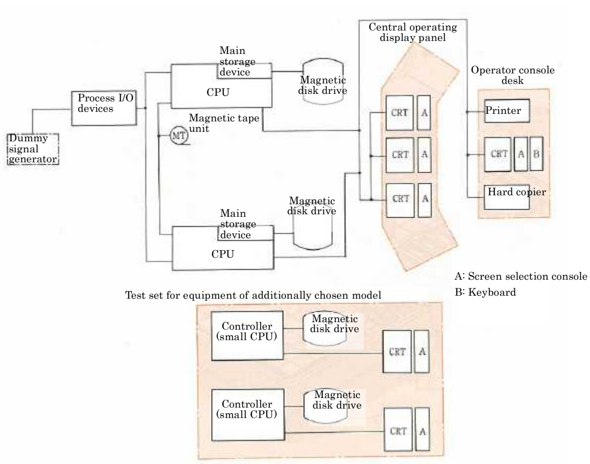


Fig. 2-3 Configuration of the computer system test specimen

Table 2-2 Specifications of major devices for the computer system test specimen

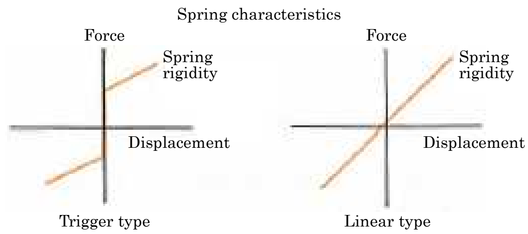
Devices	CPUs, process I/O devices, auxiliary storage devices (magnetic disk drives), CRT display units, printers, hard copies, keyboard, dummy signal generator, power supply unit, cable, enclosure, seismic isolated floor system, etc.
Computer system specifications	<Typical model> CPU: TOSBAC G 8090 x 2 Main storage device: circuit elements, LSI, CMOS gate array, IC memory 64MB x2 Aux. storage device: magnetic disk drive, 799MB x 2 CRT display: 20-inch color display unit x 4 <Additionally chosen model 1> CPU: HIDIC V90/65 x 1 Aux. storage device: magnetic disk drive, 300MB x 1 CRT display: 20-inch color display unit x 1 <Additionally chosen model 2> CPU: MELCOM 350-60/600 x 1 Aux. storage device: magnetic disk drive, 300MB x 1 CRT display: 20-inch color display unit x 1
Seismic isolated floor system specifications	Restoring force: horizontal coil spring - Trigger type (two variations) Horizontal natural period: 3 sec., 2 sec. - Linear type Horizontal natural period: 3 sec. Damping force: horizontal damper Bearing: ball bearing 
Weight of equipment on the shaking table	With the seismic isolated floor implemented: Computer system: approx. 11 tons Seismic isolated floor system; approx. 70 tons Total: approx. 81 tons Equipment on the shaking table: Computer system: approx. 11 tons Foundation: approx. 20 tons Total: approx. 31 tons

Table 2-3 Enclosure specifications

Equipment	Approximate dimensions	Weight	Devices contained by the enclosure
Enclosure for the computer of the typical model (1-a)	Width: 4,800 mm Depth: 800 mm Height: 2,100 mm	Approx.3 tons	CPU, magnetic disk drive, CRT controller, magnetic tape unit and process I/O devices
Enclosure for the computer of the typical model (1-b)	Width: 4,800 mm Depth: 800 mm Height: 2,100 mm	Approx.3 tons	
Enclosure for the computer of additionally chosen model (1)	Width: 2,266 mm Depth: 800 mm Height: 1,550 mm	Approx.0.5 tons	CPU (small), magnetic disk drive and CRT controller
Enclosure for the computer of additionally chosen model (2)	Width: 1,460 mm Depth: 665 mm Height: 1,800 mm	Approx.0.5 tons	CPU (small), magnetic disk controller, CRT controller and magnetic disk drive
Central operating display panel	Width: Approx. 7 m Depth: Approx. 2.8 m Height: Approx. 1 m	Approx.2 tons	CRT display for the computer of typical model and CRT selection console
Operator console desk	Width: Approx. 3 m Depth: Approx. 1 m Height: Approx. 1 m	Approx.1 tons	CRT display for the computer of typical model, CRT selection console, keyboard, hard copier and printer
CRT console (1)	Width: Approx. 0.7 m Depth: Approx. 0.9 m Height: Approx. 1.1 m	Approx. 0.2 tons	CRT display for the computer of additionally chosen model (1) and keyboard to be used with it
CRT console (2)	Width: Approx. 0.7 m Depth: Approx. 1.8 m Height: Approx. 1.1 m	Approx. 0.2 tons	CRT display for the computer of additionally chosen model (2) and keyboard to be used with it

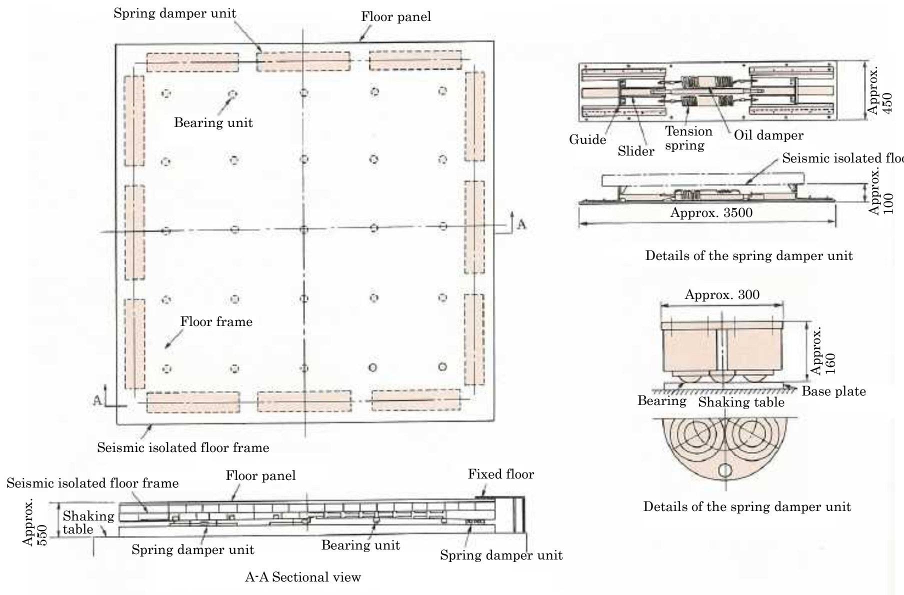


Fig. 2-4 Seismic isolated floor configuration

2.1.3 Input seismic wave, test conditions and measuring method

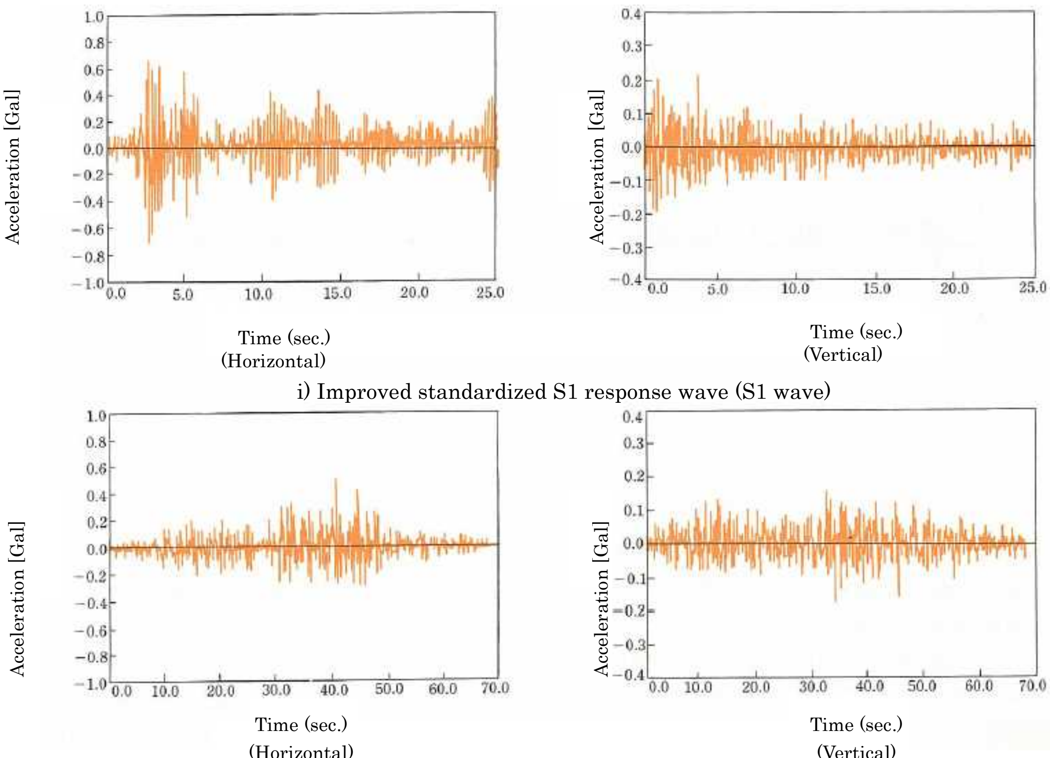
(1) Input seismic wave

As an input wave for the seismic reliability proving test on base-Isolated computer system, severest one for the computer system among the floor-level response waves was selected. Those response waves were obtained from seismic response analysis of the standard plant buildings utilizing the improved and standardized seismic wave specified by the Ministry of International Trade and Industry (MITI) as the design basis ground motion for high seismicity regions. In addition, considering vibration characteristics of the seismic isolated floor, an appropriate seismic wave which had long-period components was selected.

Table 2-4 and Fig. 2-5 describe and illustrate the input waves. In the testing of seismic safety margin, the input waves listed in Table 2-4 were magnified, increasing the acceleration of ground motion as much as possible within the capacity of the shaking table.

Table 2-4 Input Wave

	Input wave	Direction	Maximum acceleration (Gal)	Duration (sec.)	Remarks
Testing of computer system on seismic isolated floor	Improved S_1 response wave	Horizontal	526	25.0	S_1 wave
		Vertical	158		
	Long-period component evaluation wave S_1 (L)	Horizontal	492	68.0	S_1 (L) wave
		Vertical	178		



ii) Long-period component evaluation wave S1 (L)

Fig. 2-5 Time historical acceleration data of the input wave

(2) Test conditions

The shaking table reproduced a seismic response wave that is assumed to be the severest for the seismic isolated floor and the computer system placed on it in order to prove the structural integrity, strength and function maintenance of the computer system.

In the design method verification tests, test conditions were modified from the proving test in order to facilitate the collection of additional data useful to the verification and evaluation of seismic design practices:

(i) The trigger type floor isolation device springs are set to a rigidity level higher than that for the proving test.

(ii) A test was done with linear type floor isolation devices applied in order to obtain additional data useful to the evaluation of floor isolation equipment design practices.

Table 2-5 Types of tests, test objectives and vibration conditions

Test type	Objectives	Description	Oscillation conditions			Computer operating status
			Wave and vibration level	Vibration direction		
				Horizontal	Vertical	
Preliminary test	(1) Confirming validity of the setup of the test specimen and influence of electric noises, etc. on measuring instruments (2) Acquiring general information on vibration response of the test specimen to have overview of the specimen response, oscillation direction, etc., in design verification test and demonstration test (3) Identifying vibration control characteristics of the shaking table	Sine wave sweep test	Sine waves (oscillation level varied by two or three steps)	Yes	—	Non-operating
				—	Yes	
		Vibration test by seismic response waves	S_1 S_1 (L)	Yes	Yes	Operating
Design method verification test	Verifying the design practices related to the use of a seismic isolated floor	Vibration test by seismic response waves	S_1 S_1(L)	Yes	Yes	Operating
Proving test	Demonstrating the structural and functional integrity of the computer system on the seismic isolated floor	Vibration test by seismic response waves	S_1 S_1 (L)	Yes	Yes	Operating
Safety margin test	Evaluating the seismic safety margin of the computer system on the seismic isolated floor	Vibration test by seismic response waves	S_1	Yes	Yes	Operating
				Yes	—	

(3) Measuring methods

The types of data to be collected were determined with a view to enabling the evaluation of mechanical characteristics (oscillation characteristics and strength) and the monitoring of functional integrity. The functional maintenance of the computer system was verified by monitoring of output produced by the system during vibration test in response to dummy input signals. The dummy signals into the computer system were similar to the ones processed at a nuclear power plant, and validity of the output the system was verified using function maintenance verification software.

As shown in Table 2-6, the devices comprising a computer system fall into the following categories: (1) devices that operate online without requiring interventions by the operators, (2) devices that operate only when instructed by an operator, and (3) devices that operate during the execution of computer system maintenance activities. Among the devices comprising a computer system at a nuclear power plant, the devices that need to remain function during and after an earthquake are those that fall into the categories of (1) and (2) above. The function of devices which fall into the category (1) is confirmed during vibration test. As to the devices that fall into the category (2), it is necessary to verify that they remain function after the completion of the vibration. Therefore, these devices were tested by an operator before and after the vibration to verify their function.

In addition to the basic functions (pertaining to the capability to process instructions), the computer system supports the following as parts of standard functions:

(i) Error detection including data error checking, control signal checking and program overrun detection
(ii) Logging (collection and saving of information about errors and abnormalities)
(iii) Safeguard (recovery from error/abnormality)

The function maintenance verification software, therefore, was designed to test basic functions (logical/mathematical operations, I/O, data saving, etc.) of each device periodically, and was capable of immediately detecting and recording any error in the functioning of any device. The software was configured on the basis of hardware test programs used by manufacturers for the function maintenance testing of the devices.

Response acceleration, strain, displacement, etc., were measured at representational positions in the test specimen or on the shaking table. A data logging subsystem collected measurement data by receiving signals from accelerometers, strain gages, displacement gages, etc. The following measurements were taken at positions relevant to the demonstration of seismic resistance of the computer system test specimen. Table 2-7 gives an overview of the measurements.

- Computer (main unit)
  1) With each computer main unit, its vibration characteristics were determined using accelerometers installed to the bottom and top of the computer enclosure, to individual devices inside the enclosure, and to the mounting positions of these devices inside the enclosure.

2) At the bottom of each computer enclosure, the strain of the enclosure mounting bolt was measured to enable the evaluation of its strength.
3) Verification software was used to be able to monitor the execution of a predefined set of operations and to detect and record any error.

- Peripheral devices
  1) With each peripheral device, its vibration characteristics were determined using accelerometers installed to representative positions.
  2) Visual check of constant display of a test pattern was conducted in order to confirm the normal operation of the system.

- Seismic isolated floor
  1) The vibration characteristics of the seismic isolated floor were determined using accelerometers installed to representational positions.

Table 2-6 Function and devices of the computer system

Device name		Function	Main structural component	Location	Function category
Computer (main unit)	CPU	Serves as the core of computer system and takes care of all transactions related to monitoring, automat zing, computing, recording, etc.	Circuit boards	Computer enclosure	(1)
	Main storage device	Among the data needed by the CPU for the processing of transactions, stores the data that is being executed.	IC memory	Computer enclosure	(1)
	CRT controller	Exchanges data with CPU and manages data to be output to the CRTs.	Circuit boards	Computer enclosure	(1)
	Auxiliary storage device	A magnetic disk drive, capable of storing a large quantity of data, is used for the storing of programs and data.	Rotation mechanism	Computer enclosure	(1)
Peripheral device	Magnetic tape unit	Used for optionally archiving data.	Rotation mechanism	Computer enclosure	(2)
	Process I/O devices	Manages the exchange of data (I/O) with plant facilities.	Circuit boards	Computer enclosure	(1)
	CRT display unit	Displays data distributed by the CRT controller.	CRT and casing	Central operating display panel	(1)
	Printer / hard copier	Used for printing data or for creating hard copies of screen display.	Printing mechanism	Console desk	(1) (2)
	Keyboard and CRT selection console	Enables interactions with the CPU and the selection of CRT screen.	Pushbuttons	Console desk and central operating display panel	(2)
	Maintenance console CRT	Used in maintenance activities such as updating software. (The console has a display unit, a keyboard and a printer.)	-	Maintenance disc	(3)

Function categories:

(1) Devices that operate online without requiring interventions from the operators

(2) Devices that operate only when instructed by an operator, and

(3) Devices that operate during the execution of computer system maintenance activities

Table 2-7 Overview of the measurement

Measurement items	Measuring location	Objectives of measurement
Shaking table acceleration	On the shaking table	Monitoring the input acceleration produced by the shaking table.
Acceleration of the computer main unit	Computer enclosure Devices inside the enclosure and their mounting positions	Determining the vibration characteristics of the computer main unit and the devices inside the computer (main unit) enclosure
Strain to the computer enclosure	Computer enclosure	Monitoring for the evaluating the strength of the computer enclosure
Strain to the computer enclosure mounting bolt	Computer enclosure mounting bolt	Monitoring for the evaluating the strength of the computer enclosure mounting bolt
Acceleration of the central operating display panel	Peripheral devices and their mounting positions Central operating display panel	Determining the vibration characteristics of the central operating display panel and its peripheral devices
Acceleration of operator console desk and CRT desk	Peripheral devices and their mounting positions Desk	Determining the vibration characteristics of the operator console desk and its peripheral devices
Acceleration of seismic isolated floor	On the seismic isolated floor	Monitoring seismic input to the computer system and determining of the oscillation characteristics of the seismic isolated structure
Displacement of seismic isolated floor	On the seismic isolated floor and floor isolation equipment	Determining the vibration characteristics of the seismic isolated floor

2.1.4 Test results and evaluation

By vibration test using the seismic response wave S_1 (L), which contains long-period components that are severe condition to the seismic isolated floor system, and also the seismic response wave S_1, the structural and functional integrity of the computer system and the seismic isolated floor system were proved. Some examples of the test results are given below. These are results from the test using the S_1 (L) wave, which produces larger responses of the specimen.

1) Fig. 2-6 shows response spectrum of the input wave on the shaking table and the ratio of the input wave response spectrum to the target response spectrum. They show that the vibration testing was performed as intended.
2) During vibration of the proving test, the seismic isolated floor and the computer system maintained their normal functions. Fig. 2-7 shows examples of the time history of response acceleration. Table 2-8 lists the maximum acceleration measured on the test specimen at representative positions.

In the safety margin evaluation test, the input wave (S_1) used in the proving test was magnified by the factor of 5.3 times ($5.3S_1$, the greatest allowed by the capacity of the shaking table). With vibrations being given, the seismic isolated floor and the computer system maintained their normal functions. It was confirmed that the vibrations cause no abnormality to the seismic isolated floor or the computer system. Fig. 2-8 shows examples of the time history of response acceleration measured on the test specimen at test case of $5.3S_1$ input. Table 2-9 lists the maximum acceleration measured on the test specimen at representative positions at different vibration levels.

Test name	Seismic isolation T3
Input wave	S_1 (L)

Direction of vibration	Horizontal + vertical
Measuring direction	X-Z

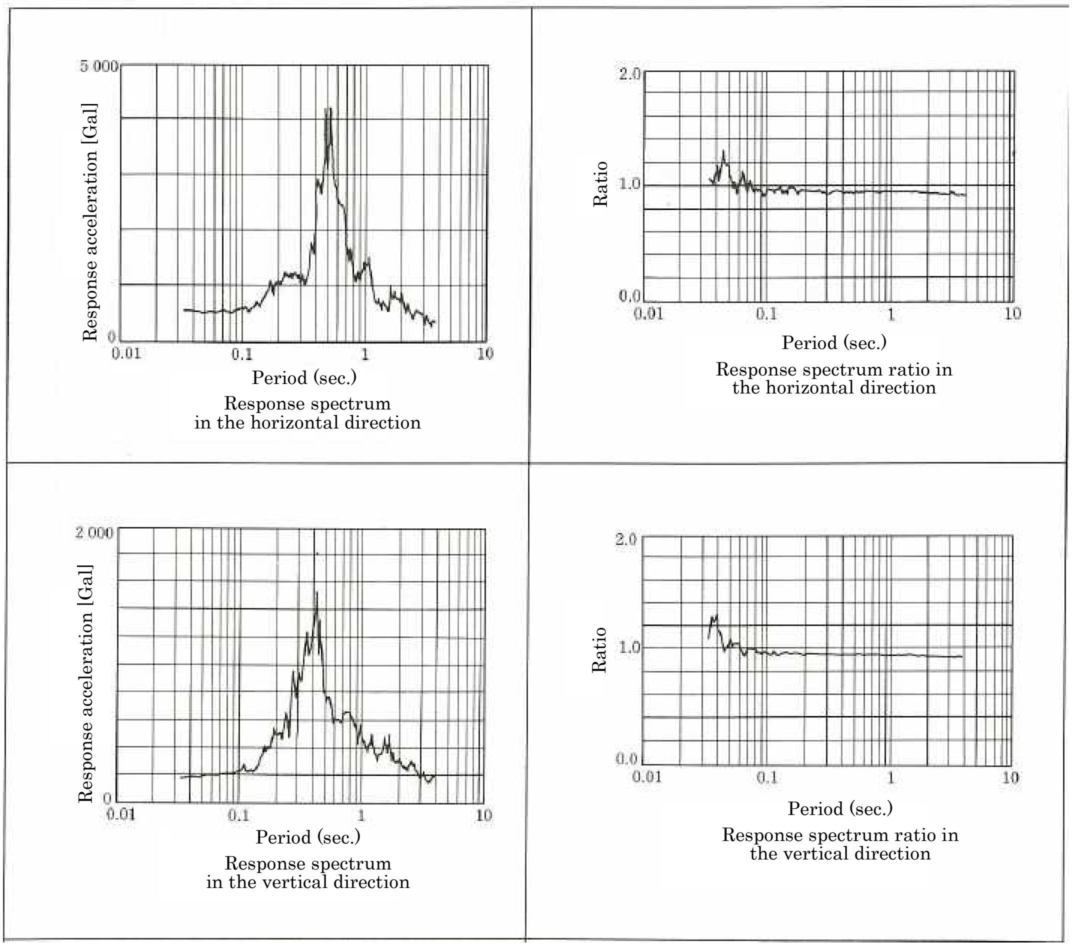
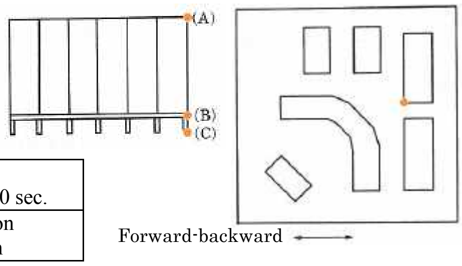


Fig. 2-6 Response spectrum and response spectrum ratio

Direction of vibration	Horizontal (forward-backward) + vertical
Measuring direction	Forward-backward

Specifications of seismic isolation system	Trigger type Horizontal natural period: approx. 3.0 sec.
S_1 (L) wave	466 Gal in the horizontal direction 181 Gal in the vertical direction



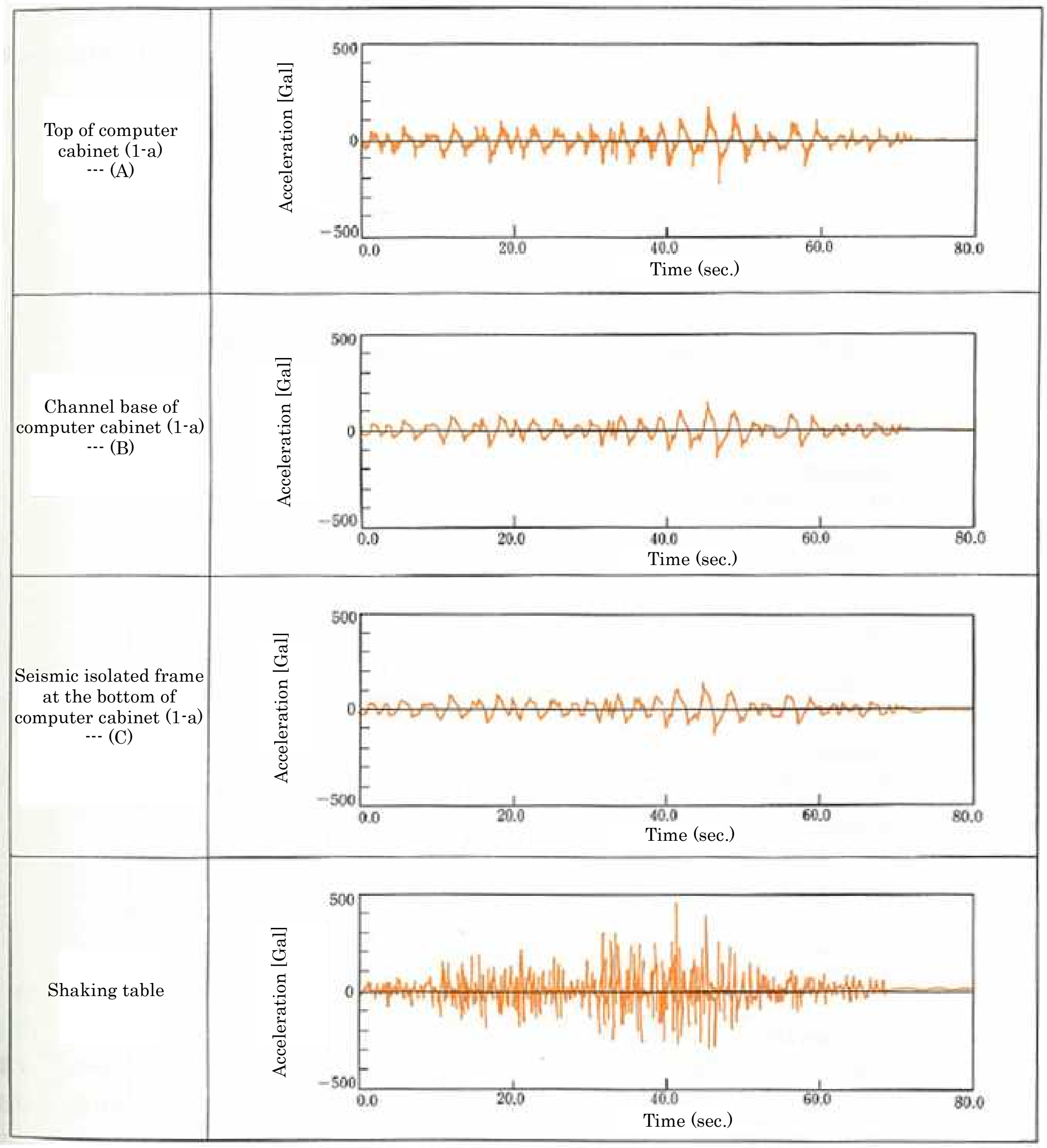


Fig. 2-7 Acceleration time history in the forward-backward direction measured on the enclosure of the computer model (S_1(L) wave)

Table 2-8 Maximum response acceleration measurement and functional integrity verification results (computer system model) (S_1(L) wave)

(Input: S_1 (L) wave)

Measuring location	Maximum response acceleration (Gal)									
	1/3*1			2/3*1			3/3*1			
	X	Y	Z	X	Y	Z	X	Y	Z	
Top of computer cabinet (1-a)	95	21	72	177	22	143	225	29	190	
Magnetic disk drive in computer cabinet (1-a)	87	41	106	150	52	187	170	61	227	
	0.06μm			0.13μm			0.15μm			Off-track measurement *3
Channel base of computer cabinet (1-a)	67	9	72	148	14	138	151	14	182	
Seismic isolated frame at the bottom of computer cabinet (1-a)	60	-	68	128	-	137	141	-	176	
Top of computer cabinet (1-b)	92	24	85	186	24	138	215	29	195	
Magnetic disk drive in computer cabinet (1-b)	81	32	140	133	11	153	162	50	262	
	0.09μm			0.17μm			0.15μm			Off-track measurement *3
Channel base of computer cabinet (1-b)	65	7	75	149	10	148	154	12	196	
Seismic isolated frame at the bottom of computer cabinet (1-b)	60	-	79	127	-	144	135	-	193	
Central operating display panel: CRT display unit	116	-	90	286	-	234	258	-	279	
Operator console: printer	87	135	131	141	144	259	165	159	263	
Input produced by the shaking table	157	-	58	336	-	128	466	-	181	

(Notes)

*1: A ratio to the target input level.

*2: The operator console desk was at the angle of 45 degrees to the direction of oscillation. Measurements were performed on each device in the forward-backward (X) and right-left (Y) directions.

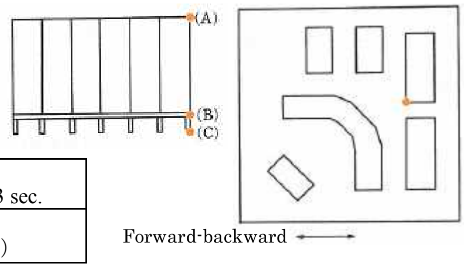
*3: This refers to the degree of misalignment of the magnetic head from the track position.

[Function maintenance verification results]

- Computer: normal operation
- CRT display unit: normal display
- Printer: normal printing operation

Direction of oscillation	Horizontal (forward-backward)
Measuring direction	Forward-backward

Seismic isolation system specifications	Trigger type Horizontal natural period: approx. 3 sec.
5.3S1 wave	2.808Gal (39 Gal in the vertical direction)



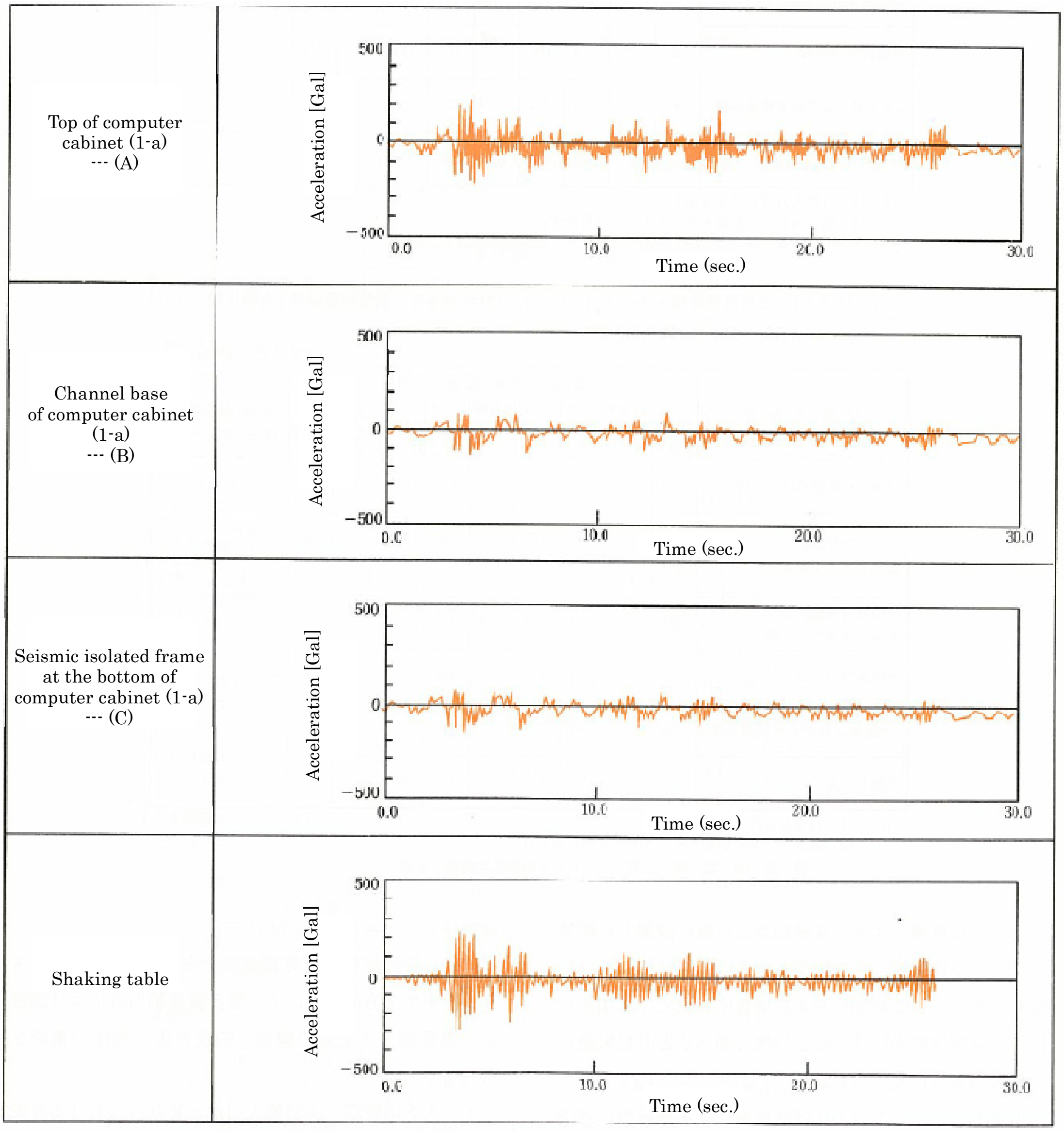


Fig. 2-8 Acceleration time history in the forward-backward direction measured on the enclosure of the computer model (5.3S_1 wave)

Table 2-9 Maximum response acceleration measurement and functional integrity verification results (computer system model) (S_1 wave)

(Input: S_1 wave, horizontal)

Measuring location		Maximum response acceleration (Gal)						
		1/3*1	2/3*1	3/3*1	2.1*1	3.3*1	4.5*1	5.3*1
Top of computer cabinet (1-a)	X	45	68	77	130	168	237	245
	Y	16	21	18	24	32	48	56
	Z	21	25	25	51	80	143	186
Magnetic disk drive in computer cabinet (1-a)	X	45	65	61	97	135	177	226
	Y	35	30	27	61	77	96	125
	Z	26	30	30	78	130	212	310
	Off-track measurement*3	0.04μm	0.06μm	0.06μm	0.08μm	0.12μm	0.18μm	0.22μm
Channel base of computer cabinet (1-a)	X	36	38	50	81	102	118	140
	Y	5	7	7	7	12	14	19
	Z	12	15	13	43	72	120	167
Seismic isolated frame at the bottom of computer cabinet (1-a)	X	33	40	45	74	91	110	128
	Z	8	15	15	39	71	113	157
Top of computer cabinet (1-b)	X	48	73	73	118	115	194	245
	Y	12	18	20	26	30	42	57
	Z	12	20	20	53	98	122	179
Magnetic disk drive in computer cabinet (1-b)	X	48	62	59	86	105	180	201
	Y	22	24	24	39	71	90	111
	Z	84	51	39	97	185	261	322
	Off-track measurement *3	0.06μm	0.06μm	0.07μm	0.09μm	0.12μm	0.22μm	0.27μm
Channel base of computer cabinet(1-b)	X	35	37	48	82	102	116	142
	Y	7	7	7	9	12	14	29
	Z	8	17	13	43	92	116	161
Seismic isolated frame at the bottom of computer cabinet (1-b)	X	31	38	44	75	89	107	131
	Z	7	13	10	42	81	108	159
Central operating display panel: CRT display unit	X	53	74	81	141	227	336	334
	Z	33	33	57	156	304	628	817
Operator console: printer	X	53	57	53	56	63	76	93
	Y	99	107	153	49	56	70	88
	Z	64	81	89	52	79	135	231

(Notes)
*1: A ratio to the target input level.
*2: The operator console desk was at the angle of 45 degrees to the direction of oscillation. Measurements were performed on each device in the forward-backward (X) and right-left (Y) directions.
*3: This refers to the degree of misalignment of the magnetic head from the track position.
- Computer: normal operation
- CRT display unit: normal display
- Printer: normal printing operation

2.1.5 Conclusion

Three types of seismic isolation floor with different characteristics were tested. All types were sufficiently capable of maintaining the response acceleration of the computer system at a level below the unified testing criterion for computer systems (250 Gal max.) against the seismic condition for the Class-A category, and availability of all types of seismic isolated floor for computer system was verified.

Furthermore, the findings from the seismic vibration testing are as follows:

1) The seismic isolated floor achieved approximately 1/3 reduction of acceleration.
2) On the seismic isolated floor, there were little coupling of horizontal vibrations and vertical vibrations.
3) There were little coupling of computer enclosure vibrations and seismic isolated floor frame vibrations.
4) While vibrations were produced using the S_1 (L) or the S_1 wave, there were no lifting of the seismic isolated floor frame.

2.2 Seismic Isolation Floor System of NIIGATA INSTITUTE OF TECHNOLOGY(NIT)/Seismic Structure Research Center(SSRC)

2.2.1 Introduction

Seismic isolation floor system of NIT/SSRC is composed of dual floor set so that seismic force is not transmitted directly to the floor that is installed in the building. The seismic isolation floor system is isolated for not only horizontal motion, but also vertical motion.

2.2.2 Outline of Seismic Isolation Floor System

(1) Composition and Function

The seismic isolation floor system is composed of supporting unit, damping devices, restoring unit and link unit. The overview of the system is shown in Fig2-9.

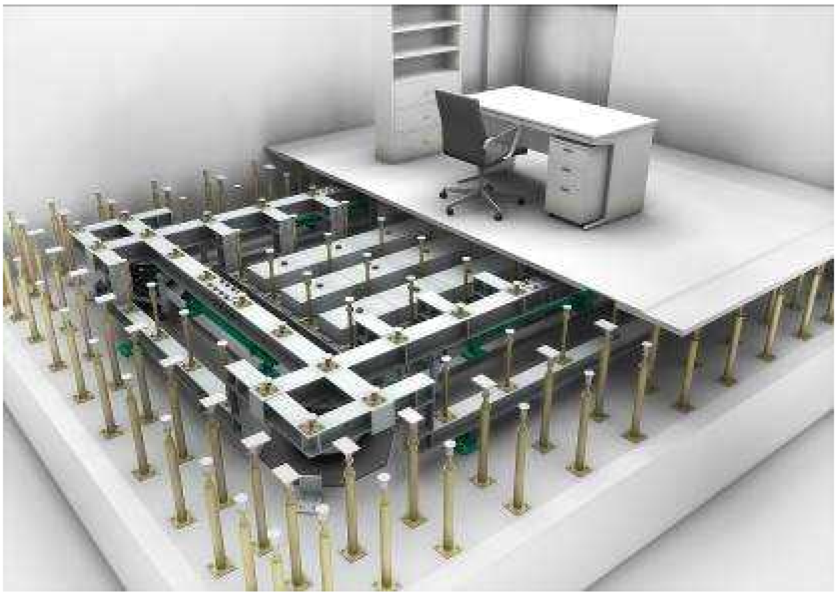


Fig.2-9 Overview of Seismic Isolation Floor System Composition

1) Supporting unit

The supporting unit consists of a ball-bearing and a compressive coil spring. Horizontal seismic acceleration is reduced by the ball-bearing, and vertical load is supported by the coil spring. Exterior of the supporting unit is shown in Fig2-10.

Fig.2-10 Exterior of supporting unit (example)

2) Damping device

The damping device is an oil damper and it reduces the relative displacement between the building-floor and the isolated-floor during an earthquake. The dampers are installed in both the horizontal and vertical directions. Exterior of the damping device (oil damper) is shown in Fig2-11.

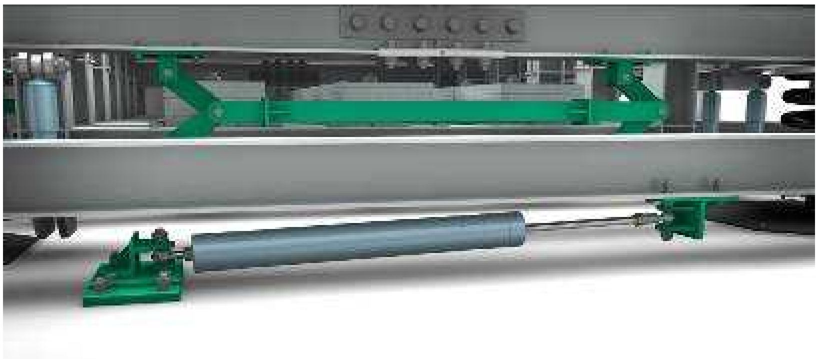


Fig.2-11 Exterior of oil damping unit (example for horizontal motion)

3) Restoring unit

The restoring unit consists of coil springs and fixtures, and works with introducing pre-tensile force into the coil springs.

This unit returns the floor back to its original position after being displaced by an earthquake. Exterior a Restoring unit is shown in Fig2-12.

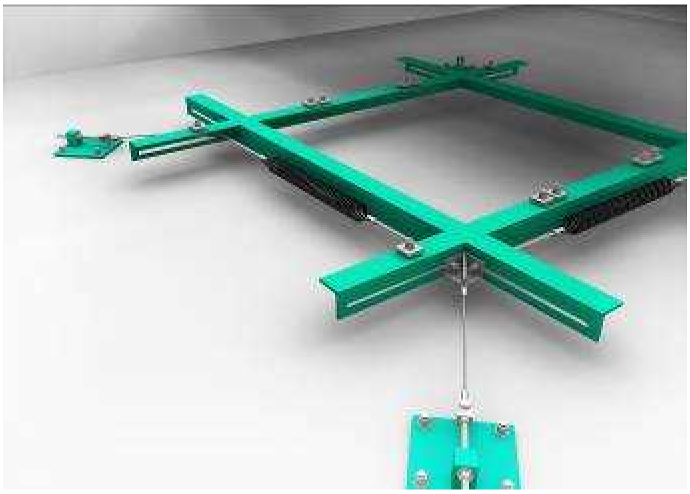


Fig.2-12 Exterior of restoring unit (example)

4) Link unit

A link mechanism has a function to keep the level of seismic isolation floor constant. Exterior a link unit is shown in Fig2-13.

Fig.2-13 Exterior of link unit (example)

(2) Main dimensions of seismic isolation floor system

Main dimensions of seismic isolation floor system are shown in Fig2-14.

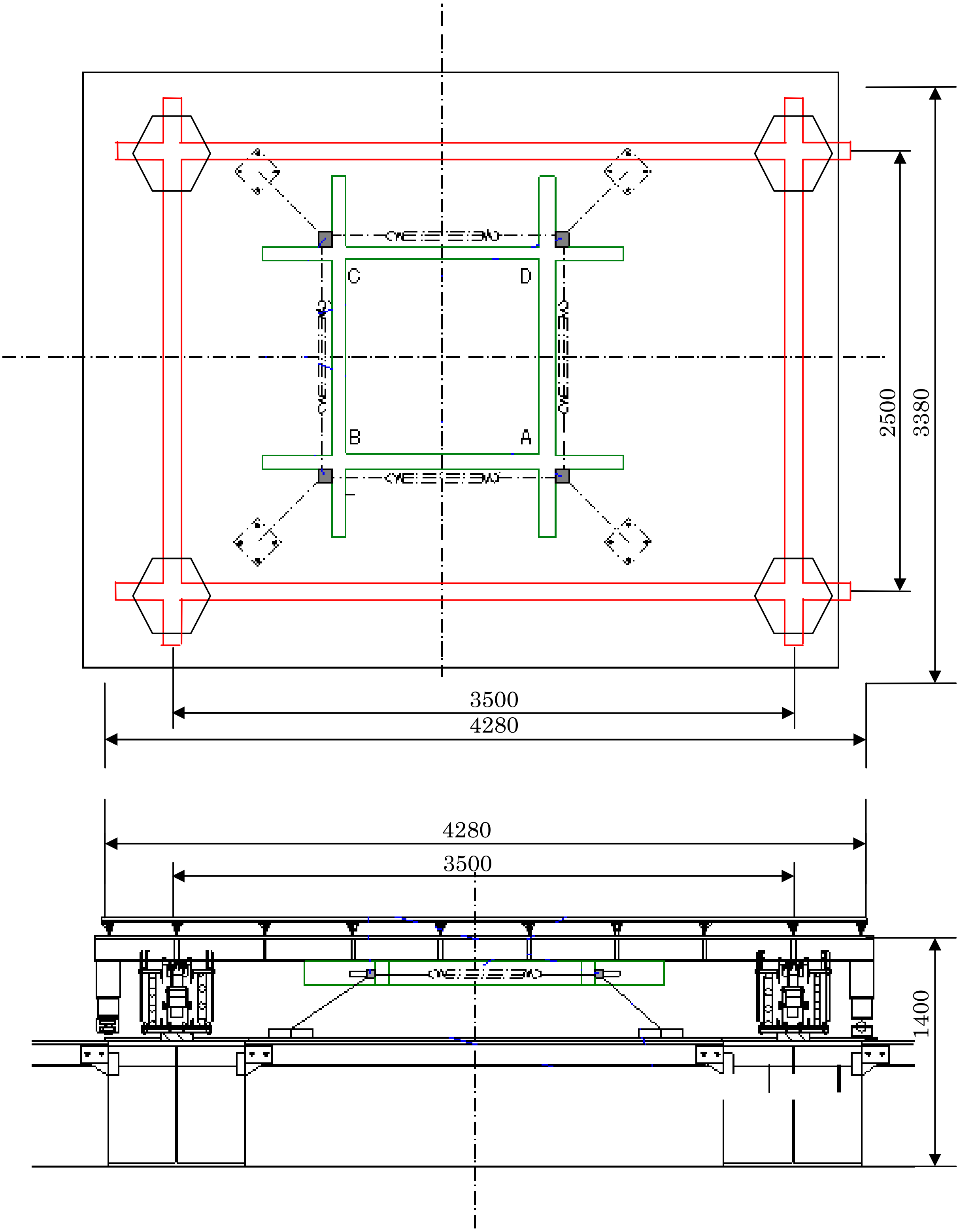
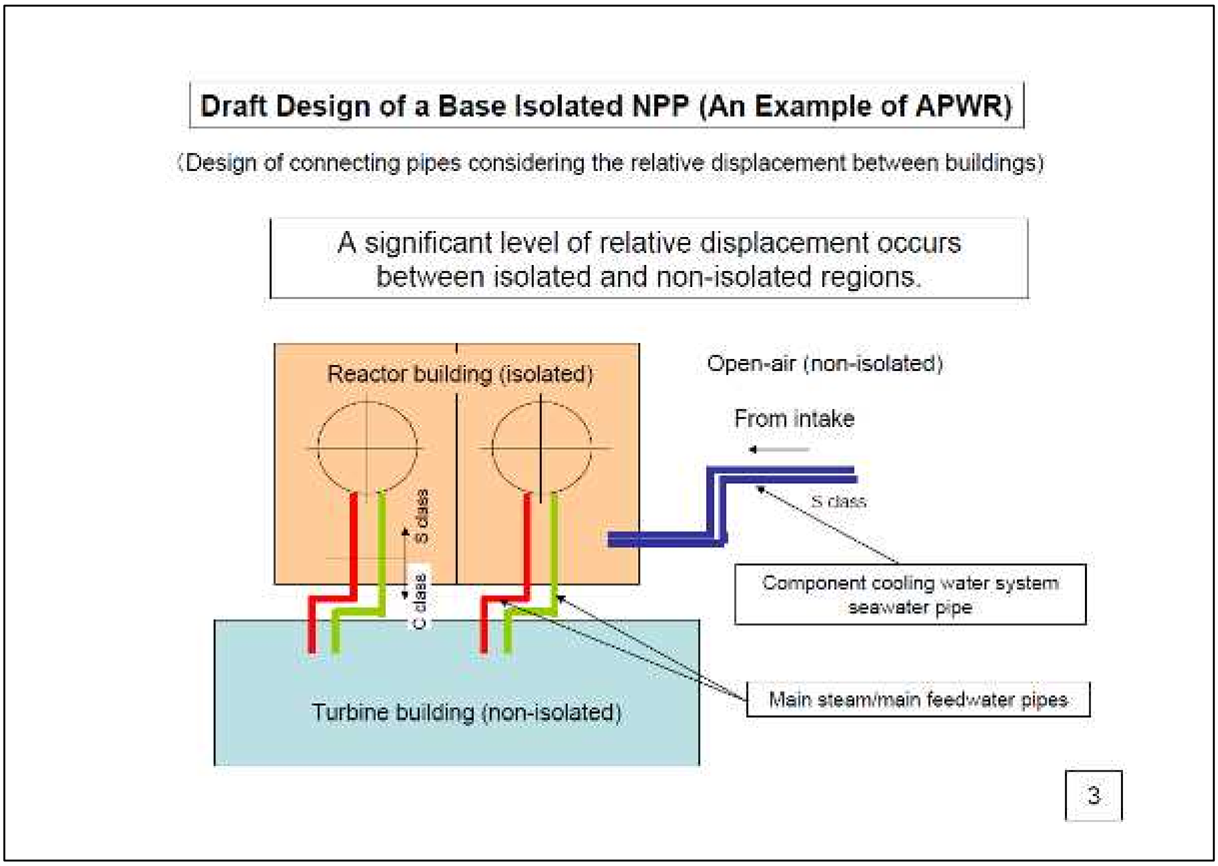
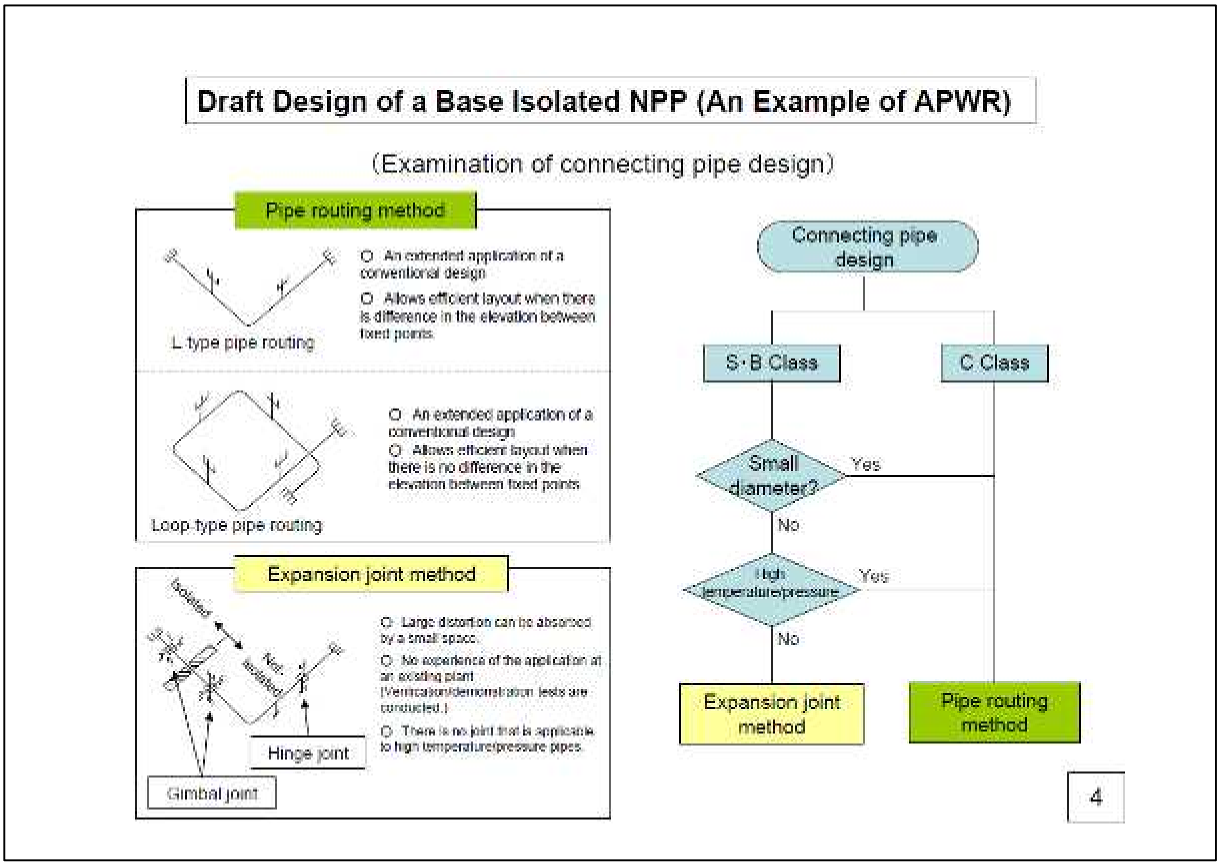


Fig.2-14 Main dimensions of seismic isolation floor system

3. Others

3.1 Design of connecting piping considering the relative displacement between buildings





Draft Design of a Base Isolated NPP (An Example of APWR)

(Design of connecting pipes considering the relative displacement between buildings)

- ○ Relative displacement between buildings is some 10 times larger than that for the earthquake resistant design plant.
- ○ In order to absorb the relative displacement 10 times higher, it is necessary to lay out the pipe having a length 10 times longer.
- ○ As the pipe length increases, inertia increases (A connecting pipe is not allowed to have a support). At the same time, pressure drop and heat loss increases, which results in a reduced heat efficiency.

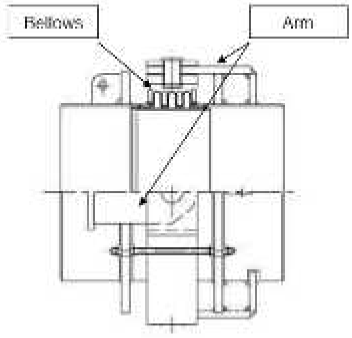
A good balance between isolation effect and relative displacement is critical.

5

Draft Design of a Base Isolated NPP (An Example of APWR)

(Application of extension joints to a connecting pipe)

Adoption of a gimbal joint (biaxial) and hinge joint (uniaxial) both of which have been already applied to operating plants



Example of Gimbal Joint

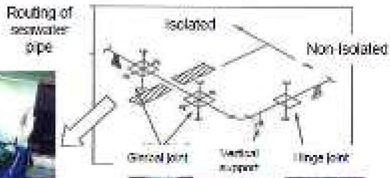
6

Draft Design of a Base Isolated NPP (An Example of APWR)

(Verification and demonstration tests of expansion joint method)

Vibration table test for pipe (4B)

Simultaneous vertical and horizontal excitations by modeling a connecting pipe



Full-scale joint mockup unit test
(28B gimbal joint)

Alternate stresses are applied by a vibration exciter

⇩

Confirm the damping constant and rotational stiffness

7

3.2 Design Example for Piping and Other Equipment in Seismic Isolated BWR Nuclear Power Plants

3.2.1 Trial Design of Common Foundation Type Seismic Isolated Building

Concerning the seismic isolated BWR nuclear power plants located in high seismicity area, the seismic isolated complex building where reactor building and associated buildings/facilities are installed on a common foundation is considered effective as a countermeasure for crossover piping against relative displacement due to earthquake.

In a basic configuration of seismic isolated complex building, a reactor building and a turbine building are installed on a common foundation in order to eliminate relative displacement of high temperature/pressure piping such as main steam piping and feed-water piping. However, in a situation where the CW (Circulating Water) pump and the RSW (Reactor Sea Water) pump are installed in a non-isolated building, large-bore CW piping and RSW piping which is in the high seismic classification are expected to serve as crossover piping between the seismic isolated and non-isolated buildings.

In this trial design, the sea water intake pumps (CWPs and RSW pumps) are also installed in the seismic isolated common foundation complex building, assuming that the above-mentioned piping system cannot absorb relative displacements by expansion joints.

Fig. 3-1 shows the conceptual drawing of the common foundation type seismic isolated complex building where the sea water intake pumps are installed on the seismic isolated foundation with large footprint.

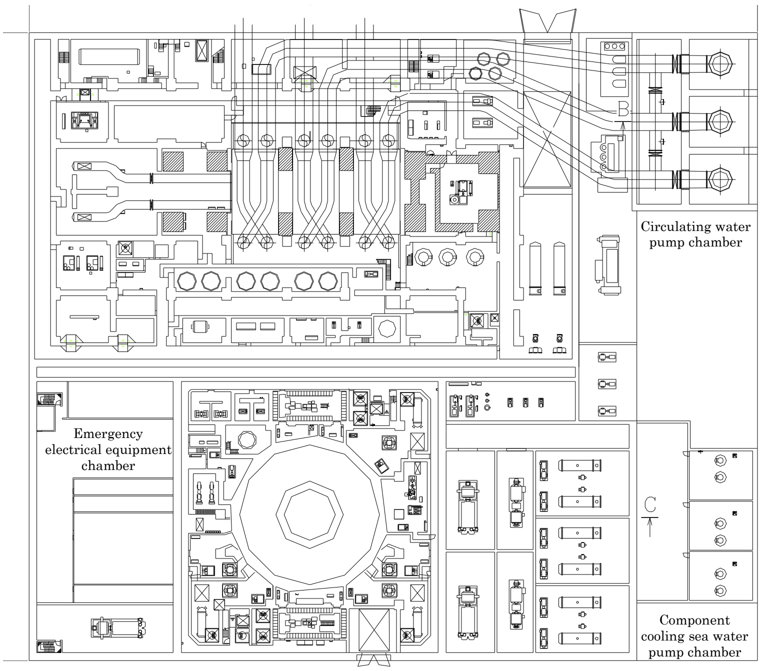


Fig. 3-1 Conceptual drawing of the common foundation type seismic isolated building

3.2.1 Layout of the Common Foundation Type Seismic Isolated Building

(1) Scope of seismic isolation

Fig. 3-2 shows the example of the connecting piping in the earthquake-proof plant. As the figure suggests, in case of common foundation type building in which the reactor building and the turbine building are installed, the large-bore CW piping and RSW piping which is categorized into high seismic classification would be still crossover piping connecting seismic isolated and non-isolated buildings. As the expected maximum displacement of seismic isolation device story was about 40cm, it was decided that the water intake pumps (CWPs and RSW pumps) should be seismically isolated assuming that the expansion joints could not absorb the relative displacements.

In terms of the isolation phase bus duct connecting the generators and the transformers, the possible absorbing relative displacement is just several dozen mm, measures to absorb relative displacements can be implemented by installing the transformers on the common foundation type building.

Acronym (Included equipment)
R/B: Reactor building (Reactor facility)
T/B : Turbine building (Turbines, generators)
Ax/B : Auxiliary building (Waste processing equipment)
Hx/B : Sea water heat exchanger building
(Reactor cooling water pumps, heat exchangers)
M.Tr: Main Transformer

Layout of the connecting piping

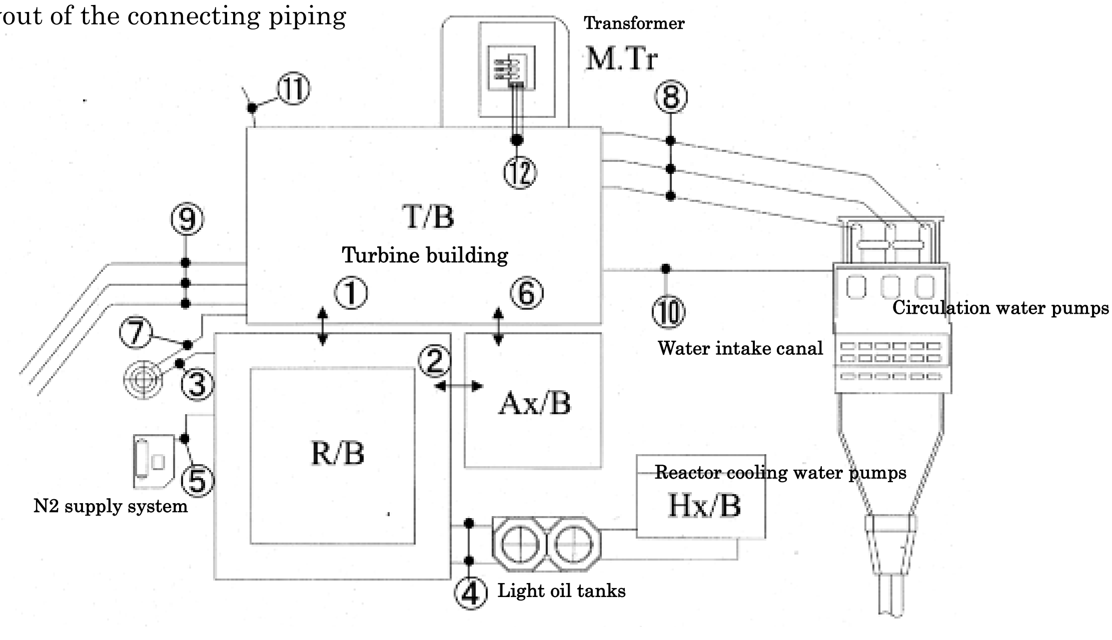


Fig. 3-2 Example of layout of connecting piping in an earthquake-proof BWR plant

Table 3-1 Example of selected seismic isolated equipment in a common foundation type building

No	Connecting piping, etc.		Expected challenges when taking measures against relative displacement	Buildings and equipment subject to seismic isolation
①	Main steam/feed-water piping	R/B～T/B	High temperature/high pressure pipes	R/B,T/B
②	Waste treatment system piping, etc.	R/B～Ax/B		
③	Piping connected to the main stack	R/B～Main stack		
④	Reactor cooling water piping	R/B～Hx/B	S class pipes	Hx pumps
⑤	Piping connected to the outside equipment			
⑥	Waste treatment system piping, etc.	T/B～Ax/B		
⑦	Piping connected to the main stack	T/B～Main stack		
⑧	Circulation water piping (intake)	T/B～Sea water intake canal	Large-bore pipes	Circulation water pumps
⑨	Circulation water piping (discharge)	T/B		
⑩	Non-safety sea water system piping	T/B～Sea water intake canal		
⑪	Connecting piping	T/B～ Adjacent unit		
⑫	Isolation phase bus duct	T/B～M.Tr	Allowable displacement: small	Transformers

(2) Plot plan, building layout plan

a. Site condition

The followings are the site conditions assumed when preparing a trial design of the common foundation type seismic isolated complex building:

- Design basis ground motion

  Horizontal acceleration：800Gal

  Vertical acceleration：533Gal

- Soil characteristics

  Shear-wave velocity：700m/s

b. Examination of the plot plan

Fig. 3-3 shows the plot plan of the common foundation type seismic isolated complex building including the CWPs and the RSWPs in the base isolated area, as was explained in the section of the scope of seismic isolation.

In this draft plot plan, the amount of material associated with the connecting piping was reduced by arranging the CWPs connected to the turbine building (condenser) on the side of the turbine building (condenser) and arranging the RSWPs to cool the reactor system adjacent to the reactor building. In addition, in this draft plot plan, the transformers are installed on the common foundation on the side of the generators in the turbine building.

The followings are the major items to be taken into consideration in the plot plan:

- Auxiliary building (equipped with access control system) is located near the C/B (Control Building) in consideration of easier personnel access.
- Interface sections of the piping connecting the seismic isolated and non-isolated buildings, except the high temperature/pressure piping, seismically important piping and large-bore piping, are concentrated by grouping the outside facilities as much as possible.
- Besides those mentioned above, the main stack and the light oil tanks are located to be near the relevant facilities on the side of the common foundation type seismic isolated building.
- The cranes are designed to be able to easily access during construction.

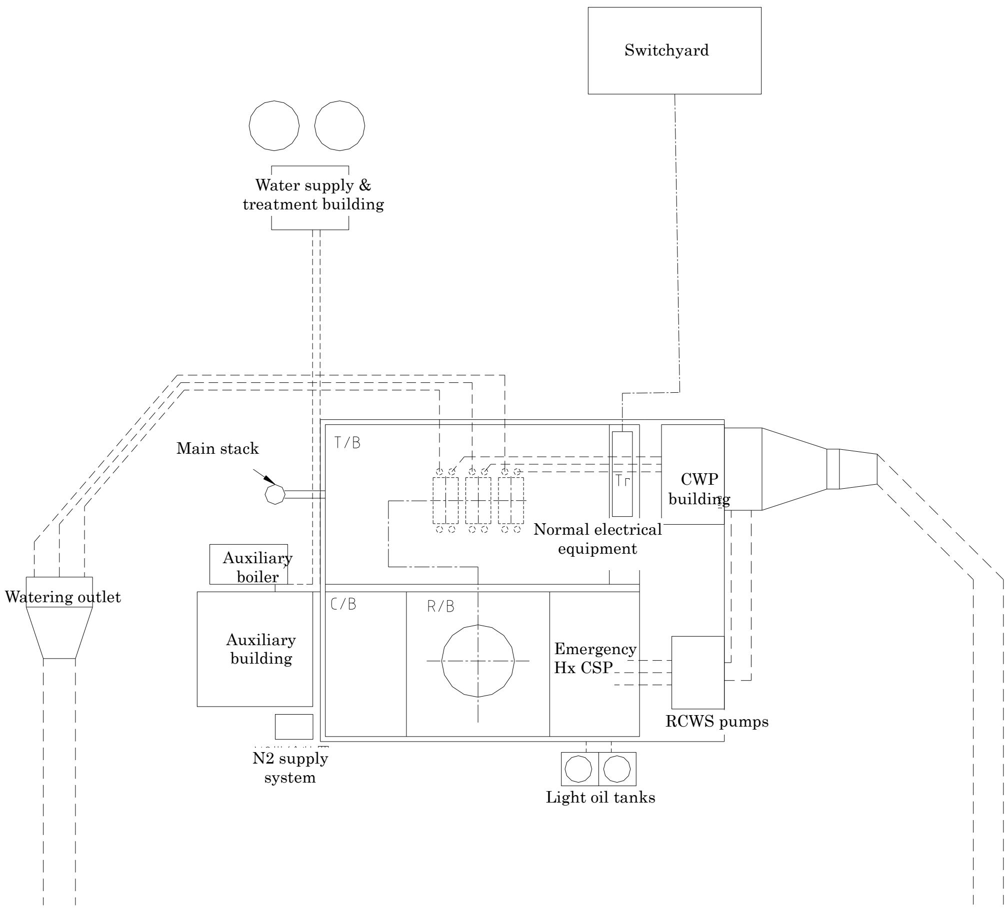


Fig. 3-3 Plot plan of seismic Isolated BWR nuclear power plant for a BWR site

c. Building layout plan

The layout of the common foundation type seismic isolated complex building was designed by arranging the following buildings and equipment on the common foundation, based on the examination of the scope of seismic isolation and the plot plan.

Fig. 3-4 shows the layout of the common foundation type seismic isolated complex building:

① Reactor building
② Turbine building
③ Control building
④ Circulation water pumps (CWPs)
⑤ Reactor sea water pumps (RSWPs)/Reactor cooling water heat exchangers (RCWHxs)
⑥ Transformers

The plant areas are grouped into the reactor building area and the turbine building area. Considering reduction of the length of the piping and cables connecting the reactor facility and other equipment, the reactor facility, emergency electrical equipment, main control room (located on the upper floor of the emergency electrical equipment room), emergency diesel generators and the associated air-conditioning units, the CWPs and RCWHxs to cool these components are installed in the reactor building area. The turbine building area includes the turbine equipment, CWPs and transformers.

Although the walls between the reactor building area and the turbine building area could be structurally integrated, it was decided that they have separate structures to keep mutual features of building configuration such as column span and floor level, and so that the construction works in each area could be carried out in parallel. Also, it was designed that the space between the reactor building area and the turbine building area could be effectively used as a working space during construction, as personnel access space and the piping space after completion of construction.

Based on the above examination, the dimensions of the common foundation type seismic isolated building were determined to be approximately 130m ×150m.

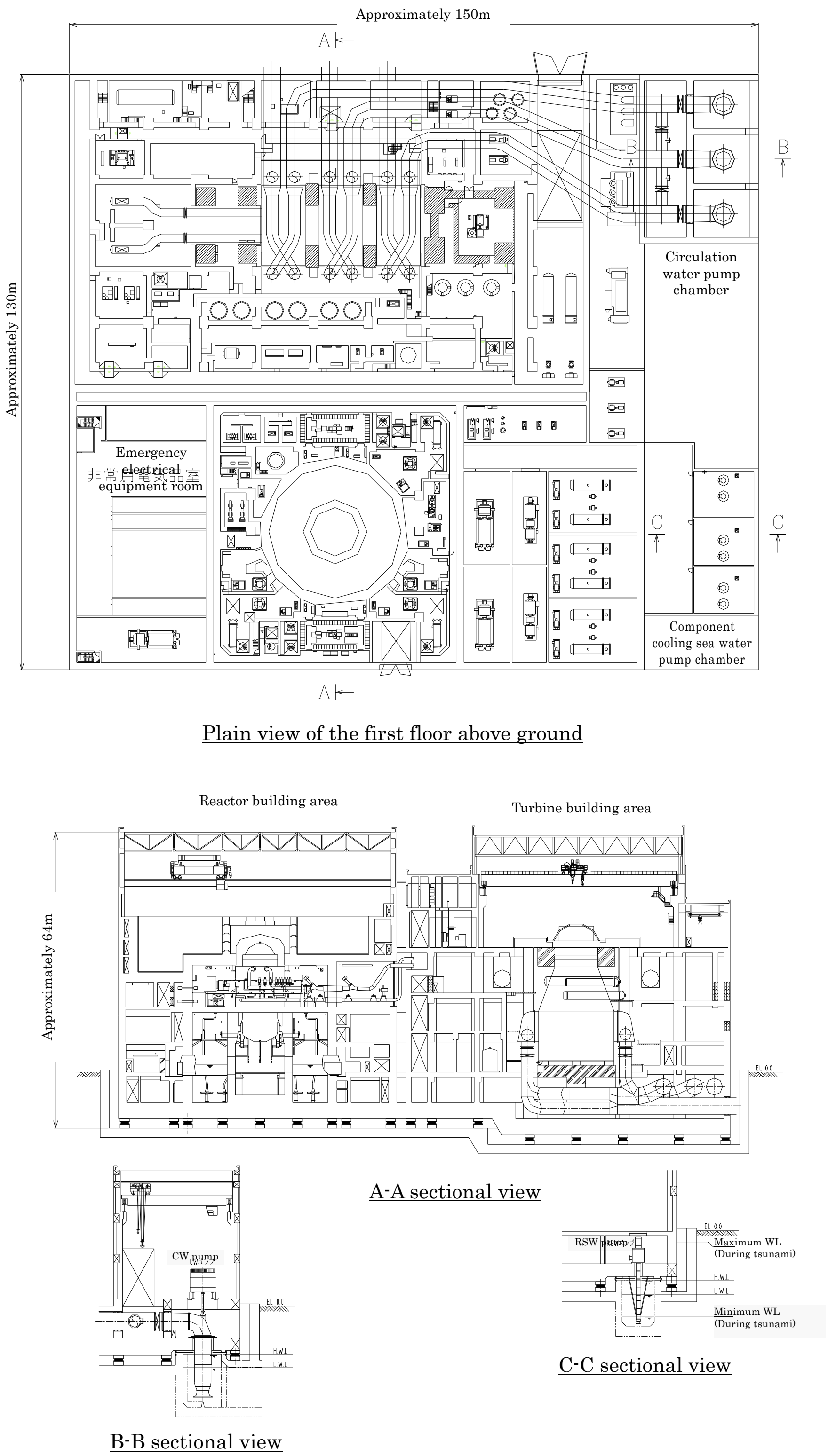
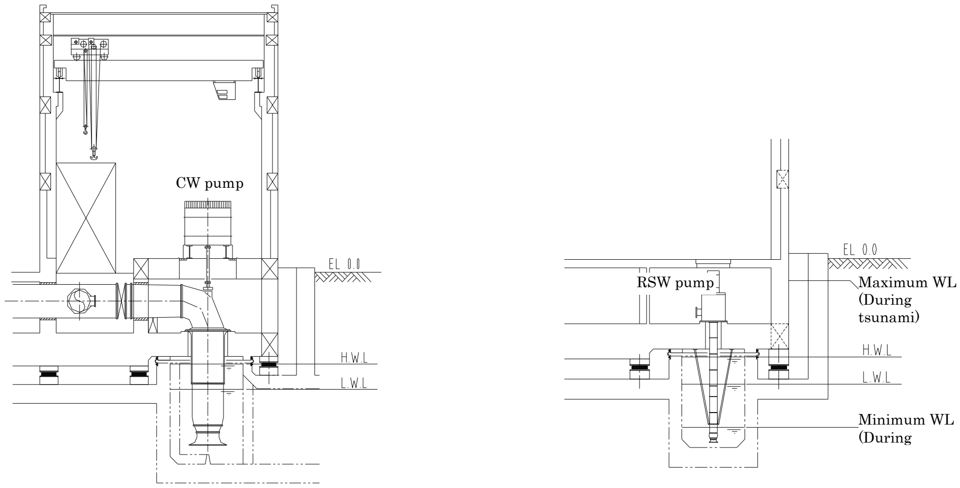


Fig. 3-4 Layout of the common foundation type seismic isolated complex building

(3) Interface between the common foundation type seismic isolated complex building and the sea water intake/discharge structure

In case where the sea water intake pumps (CWPs and RSWPs) are installed in the seismic isolated building, the crossover piping (CW piping and RSW piping designated as high seismic classification) can be deleted as was previously mentioned. However, relative displacement would be generated between the sea water intake canal serving to introduce sea water into the sea water intake pumps and the common foundation type seismic isolated complex building. Therefore, the interface structure was examined in order to ensure intake of sea water on a stable and reliable basis.

Fig. 3-5 shows the interface structures between the CWP/RCWP area and the sea water intake canal area.



CWP area　　　　　　　　　　RSWP area

Fig. 3-5　Interface structures of pump areas and the sea water intake canal

The interface structure was designed based on the following concepts:

- The vertical shaft is designed in the water intake canal as interface structure between CWPs/RSWPs areas and the canal in consideration of easier structural separation. Moreover, joints are installed at the sections where displacement is occurred.
- Sealing method is to be planned based on the use of the M-type joints, which are popularly used in the normal civil engineering structures. Joints are also installed outside the above-mentioned vertical shaft to allow maintenance work.
- The sealing point is decided to be equal or higher than high water level (HWL) to ensure integrity of the seal (M-type joint).
- The seal must keep its integrity even under the static and dynamic sea water pressure in the event of tsunami because the sea water level of tsunami is expected to be higher than the above-mentioned seal point.
- The pump barrel shall be fixed by supporting structures from the side of the seismic isolated building if necessary because the pump barrel is cantilevered from the side of the seismic isolated building. The horizontal clearance between the pump barrel (including the supporting structures) and the vertical shaft of the sea water intake

canal must be not less than the ultimate displacement of the isolator and also not less than the installation work space of the pump barrel so as to avoid interference of the pump barrel and the vertical shaft of the sea water intake canal during and after plant construction.

(4) Clearance gap of the sea water intake canal structure

The clearance between the superstructure and the surrounding walls, etc. is decided to be not less than the ultimate displacement of the isolator, assuming the occurrence of the beyond design earthquake.

Specifically, the clearance between the superstructure and the surrounding walls are set to be not less than 1040mm (entire thickness of rubber bearing 260 mm × fracture strain 400%) to prevent impacts prior to the fracture of the isolator.

・Clearance between the superstructure and the surrounding walls：2000mm

・Clearance between the pump barrel (including supports) and the vertical shaft section of the sea water intake canal：1100mm

(5) Conclusion

Trial design was developed for the common foundation type seismic isolated complex building where the reactor building, turbine building and sea water intake pumps, etc. were installed on the common seismic isolated base as a measure to absorb relative displacements generated in the high seismicity zone. The proposed design was developed based on the site conditions including soil characteristics, ground motion and the sea water level at the concerned site.

The basic measures for the common foundation type seismic isolated BWR plant to absorb relative displacements during earthquakes were developed. Specifically, the plot plan, the building layout plan on the seismic isolated foundation base, the interface structure between the common foundation type seismic isolated building and the sea water intake canal, where the relative displacements would be generated during earthquakes, and clearance between the superstructure and the surrounding walls were designed

iii. Examples of Trial Assessment of Seismic Isolation Structure

1. Evaluation of Failure Probability of Equipment Isolation for Nuclear Facilities

JCOSSAR2007

Development of the Methodology for Evaluating the Probability of Failure of Seismic Isolation System for Nuclear Components

Hideaki TSUTSUMI* Katsumi EBISAWA* Masahide SUZUKI**
Hiroyuki YAMADA*** Shigeru FUJIMOTO****
* Japan Nuclear Energy Safety Organization (JNES)
** Japan Atomic Energy Agency (JAEA)
*** National Research Institute for Earth Science and Disaster Prevention
**** Shonan Institute of Technology

1. Introduction

Seismic isolation is identified as one of the techniques that can contribute effectively to the lowering of risks associated with damages to nuclear power plants that can be caused by an earthquake. Seismic isolation techniques are classified by scope into building isolation, floor isolation and equipment isolation (or "component base isolation"). Among them, component base isolation is appreciated as a practical solution for lowering the earthquake risks because it can be implemented at a relatively low cost both at newly constructed plants and at existing plants.

The Japan Atomic Energy Agency (formerly the Japan Atomic Energy Research Institute) has been applying the methodology of seismic Probability Safety Assessment (S-PSA)[1] to the evaluation of component base isolation technique, has developed a method[2] and evaluation analysis code[3] for the evaluation of the effectiveness of protecting a safety critical component (one identified as such by S-PSA) by a horizontal seismic isolation device, and has proposed a method for evaluating the economic efficiency of component base isolation technique. In addition, the agency has conducted a case study concerning the seismic isolation of start-up transformer with porcelain bushing, which is identified as a component important to safety, and demonstrated that the seismic isolation technique, in this case, is a highly economical solution that greatly lowers the component failure probability.[4] [5] Furthermore, the agency designed and fabricated two- and three-dimensional component base isolation systems[6], tested them on a shaking table and observed their responses to natural ground motions to determine their dynamic characteristics and their seismic isolation capabilities,[7] [8] demonstrating the validity of the proposed methods.

On the basis of outputs from the research activities mentioned above, the authors have proposed a probabilistic approach to the evaluation of component base isolation design consistent with the safety goal[9] of the nuclear facility currently being discussed within the Nuclear Safety Commission, and developed a method for the evaluation of the effectiveness of component base isolation at a nuclear power plant.[10] This evaluation method consists of the steps of earthquake risk evaluation, evaluation of actual response of component, evaluation of function limit of component, failure bribability assessment and reliability analysis. Among these targets, function limit and failure probability are conventionally evaluated focusing on failure of main body of the component. In the case where component base isolation is implemented, while the seismic response acceleration of the component is significantly reduced, the locating of failure and the determination of failure mode may become more difficult due to the need to give attention to a greater number of structural elements including those comprising the seismic isolation system and the complexities involved in handling interactions or interferences with nearby components. With any shortfall in design practices, the seismic isolation system may include some fragility that contributes to smaller decrease of the probability of failure of component. Therefore, careful evaluation is required.

In consideration of the above, the authors propose a method that enables detailed assessment of the probability of failure of a seismic isolated component by means of fault tree (FT) analysis. This method involves the use of a fault tree as a means to represent the relationships among the elements comprising the seismic isolation system, the identification of elements that are critical to the failure probability assessment, and the determination of the probability of failure of each of such elements. This paper contains an example of implementing this method for assessing the probability of failure of a safety critical emergency diesel generator (DG). In this example, the results of fault tree analysis were used for correcting the design of the component base isolation system as a whole by removing vulnerabilities in order to reduce the probability of failure. In addition, this paper describes a fracture limit test performed on specimens of multi-layer laminated rubber bearing, which can serve effectively as a horizontal isolation device for component base isolation, and presents the fracture limit curve derived from the test results.

2. Overview of the Component Base Isolation Effectiveness Evaluation Method and the Failure Probability Assessment Method

In order to clarify the role and purpose of the failure probability assessment method, this section presents an overview of evaluation method of the component base isolation effectiveness, and then describes the failure probability assessment method.

2.1 Overview of the Component Base Isolation Effectiveness Evaluation Method

One of the severest accidents that can happen at a nuclear power plant is core damage accident, and the core damage frequency (CDF_{target}) is defined as one of supportive indicators evaluated in connection with the safety goal for nuclear power generation facilities. When designing the component base isolation system for components important to safety, the target performance (e.g. acceleration reduction capability) of the component base isolation system is set in such a way that the core damage frequency of non-isolated power plant ($CDF_{without}$) would be below the level that justifies the safety goal (CDF_{target}). The verification of the effectiveness of the chosen design (in bringing down the CDF) should be evaluated using a method based on the approach of S-PSA.

Fig. 1 presents an overview of the CDF evaluation procedure. The procedure includes the steps of earthquake risk evaluation, soil/building/component response evaluation, function limit evaluation of component, failure probability assessment and system reliability analysis. Finally, the CDF is calculated using the following expression:

$$CDF = \int_0^{\alpha} \left[\frac{-dH(\alpha)}{d\alpha} CDP(\alpha) \right] d\alpha \qquad (1)$$

where,

H(α) (times / year): exceedance probability of α (α: a parameter of ground motion, such as the maximum acceleration, measured on free rock surface)

CDP(α): the core damage frequency corresponding to α

CDP(α) is calculated using the expression below as the sum of the probabilities of all possible event sequences that are assumed to result in core damage:

$$CDP(\alpha) = \sum_{i=1}^{n} ESP_i(\alpha) \qquad (2)$$

$ESP_i(\alpha)$ is determined by the event tree (ET) analysis utilizing ET which shows event scenarios and $SFP_j(\alpha)$, the failure probability of the mitigation system j modeled inside the event tree. $ESP_i(\alpha)$, as shown in Fig. 1, is determined by the fault tree (FT) analysis utilizing fault tree which shows scenarios of component failure and $CFP_k(\alpha)$, the failure probability of the component k modeled inside the fault tree. $CFP_k(\alpha)$ is calculated using the expression below as the conditional probability of f_k^R (α, x), the actual response of the component k, which exceeds the function limit f_k^C (x).

$$CFP_k(\alpha) = \int_0^{\infty} f_k^R(\alpha, x) \left[\int_0^x f_k^C(x) dx \right] dx \qquad (3)$$

In this expression, x is a parameter such as acceleration and stress that concerns the seismic capacity. f_k^R (α,x) and f_k^C (x) are given by the following expressions assuming that they are represented by mutually independent logarithmic normal distributions:

$$f_k^R(\alpha, x) = \frac{1}{\sqrt{2\pi}\,\beta_k^R\, x} \exp\left[-\frac{\left(\ln x - \ln M_k^R\right)^2}{2\beta_R^2} \right] \qquad (4)$$

$$f_k^C(x) = \frac{1}{\sqrt{2\pi}\beta_k^C\, x} \exp\left[-\frac{\left(\ln x - \ln M_k^C\right)^2}{2\left(\beta_k^C\right)^2} \right] \qquad (5)$$

M_k^R and β_k^R are the median and logarithmic standard deviation of f_k^R (α,x) ; M_k^R and β_k^R are the median and logarithmic standard deviation of f_k^C (x).

The methods for the evaluation of failure probability include the safety factor method[11)] and response factor method,[1)] with which the median and variation of actual response and seismic capacity are determined in reference to design basis response, and the detailed evaluation method,[12)] which gives attention to the frequency characteristics of the input seismic wave and also to the nonlinear responses of structural elements and components, and addresses variations in bedrock characteristics, material properties, etc., by the use of the Monte Carlo method, for example.

2.2 Failure Probability Assessment Method of Equipment Isolation System

A component base isolation system normally comprises a main component (plant equipment), seismic isolation device, and connecting structures around the component. When determining the component failure probability using Expression (3), the additional complexity of the system gives rise to the possibility of multiple elements and structural members seriously impacting the component failure probability. Therefore, it becomes necessary to consider the influences of such elements and structural members on the entire system, as well as different combinations of their influences. Therefore, when calculating the failure probability according to the procedure described in Fig. 1, an intelligent method was developed using a fault tree (FT) to be able to identify vulnerabilities in the equipment isolation system and critical failure modes, so as to be able to accurately determine the failure probability. Fig. 2 shows the evaluation procedures involved.

With this method, the first step is to produce a block diagram of all structural elements of the component base isolation system to facilitate the identification of elements or structural members of which damage may directly lead to the failure of the main component. This is followed by the definition of failure modes and function limits in the contexts of such failure scenarios. For each of the elements and structural members found to be critical, a scenario of its vulnerability leading to the failure of the main component should be produced. By putting together such scenarios and clarifying the relationships among them, the FT is produced. In the assessment procedure, the evaluation of actual response is performed in consideration of the failure modes identified by the fault tree and the failure probability is determined by the FT analysis.

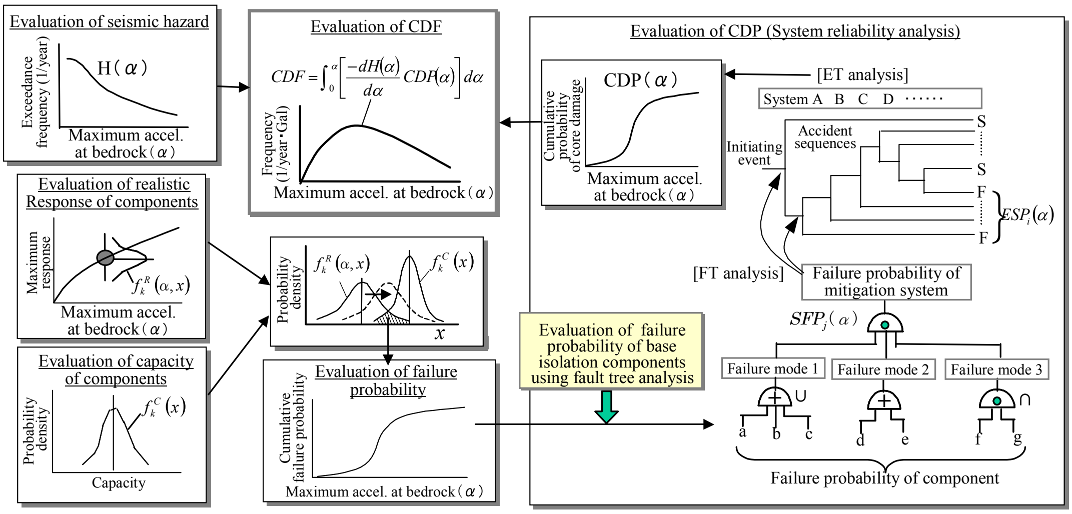


Fig.1 Procedure for effectiveness evaluation of base isolation components using seismic PSA

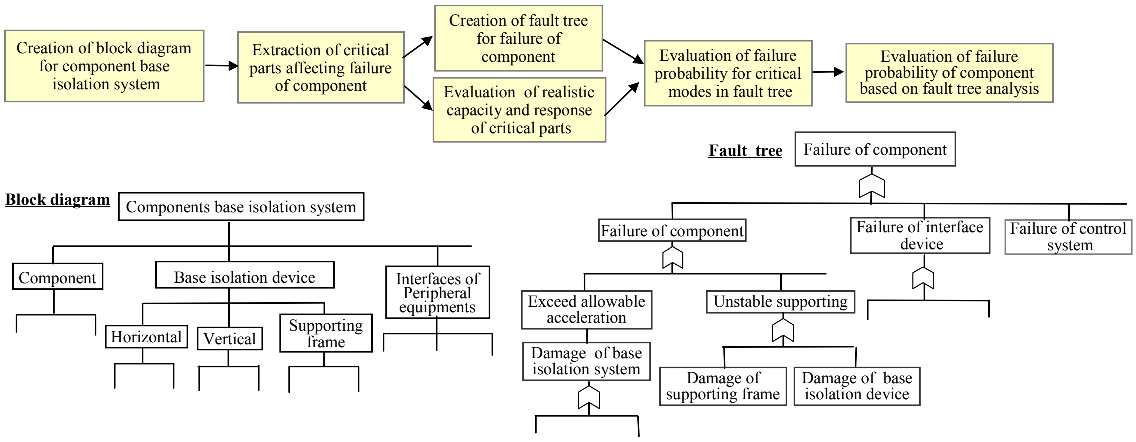


Fig.2 Procedure for evaluation of failure probability of base isolation components using fault tree analysis

3. Components to Which Equipment Isolation is Applied and Example of Fault Tree Preparation

3.1 Selection of Seismic Isolated Components and Isolation Devices

(1) Approach to the selection of seismic isolated components and isolation devices

The components seismic isolation would apply are selected from safety-related components that are of great importance in the assessment of the core damage frequency. An importance analysis, performed on a 1100MW-class BWR standard model plant of the improved Mark II type, indicated that start-up transformer with porcelain bushing (CTF), emergency diesel generator (DG), motor control center (MCC), etc., were critical components. The weight of these components is in the range between 1tf and 120tf. The weight of the component should be considered when selecting the type of seismic isolation device to be used.

Table 1 lists the application concepts of base isolation devices according to the results of design and testing conducted by the authors, etc.[7) 8)]

Ready-made products of laminated rubber bearings are the commonest choice of horizontal isolation devices. In the case of component base isolation, however, these are applied only a large component heavier than 100tf (e.g. emergency DG) as the table shows. For the seismic isolation of a medium-size component (15tf - 150tf), it is useful to make use of multi-layer laminated rubber[13)] because the use of more than one small laminated rubber elements enable the adjustment of the stiffness of the device in the horizontal direction. Slide bearing is an example of devices that can be applied to a variety of plant components ranging from heavy to light ones (e.g. electrical instrumentation panel). As to the choice of devices for vertical isolation, the use of mechanical springs is recommended because of their stability, durability and maintainability. As to dampers, the use of oil dampers with linear characteristics is useful because of the ease of adaptation for a wide variety of plant components with different characteristics.

(2) Example of base-isolated component

An emergency DG, which requires the handling of complexities regarding interactions and interferences with nearby components, was selected as the component the seismic isolation is applied to. The following describes design example of three-dimensional seismic isolation and FT example to evaluate failure probability.

3.2 Example of Seismic Isolation of Emergency Diesel Generator

(1) Overview of seismic isolation structure

Fig. 3 shows an example of three-dimensional seismic isolation of an emergency DG. The emergency DG is composed of a diesel engine and a generator, and is connected with fuel, intake and exhaust pipes. The equipment weighs about 120tf. The diesel engine and generator are mounted on a seismic isolated steel base. The three-dimensional isolation of the base is achieved by eight multi-layer laminated rubber bearings (as horizontal isolation devices) and eight coil springs (as vertical isolation devices). Eight oil dampers are used: four applied in the horizontal direction and four applied in the vertical direction. Fuel intake and exhaust pipes are applied with flexible joints having universal type bellows. The specifications of these devices and components are described in the paragraphs below.

stabilizer plates give stability against vertical load and the stacking of multiple layers enables to decrease the natural frequency in the horizontal direction.

In this example, as shown in Fig. 3, the diesel generator is supported using eight multi-layer laminated rubber bearings, and each composed of multiple elements of laminated natural rubber. Each bearing can support the load of about 20tf. The design target concerning the natural frequency in the horizontal direction is 0.4Hz (2.5 sec.). The function limit (ultimate displacement) for the multi-layer laminated rubber was determined using the test data and the evaluation procedure of the ultimate displacement described below in Section 4.

Table 1 Application of base isolation device

Installation location	component	Weight (tf)	Base isolation device			
			Horizontal			Vertical
			rubber bearing	Multilayerd rubber bearing	Slide bearing	Mechanical spring
In door	EDG	120	○	○	○	○
	EHE	100	○	○	○	○
	MCC	1			○	○
Out door	CTF	80	○	○	○	○
	CT	40		○	○	○

EDG---Emergency diesel generator CTF---Emegency transformer
EHE---Emergency heat exchenger MCC---Motor control center
CT ---Coversion tank

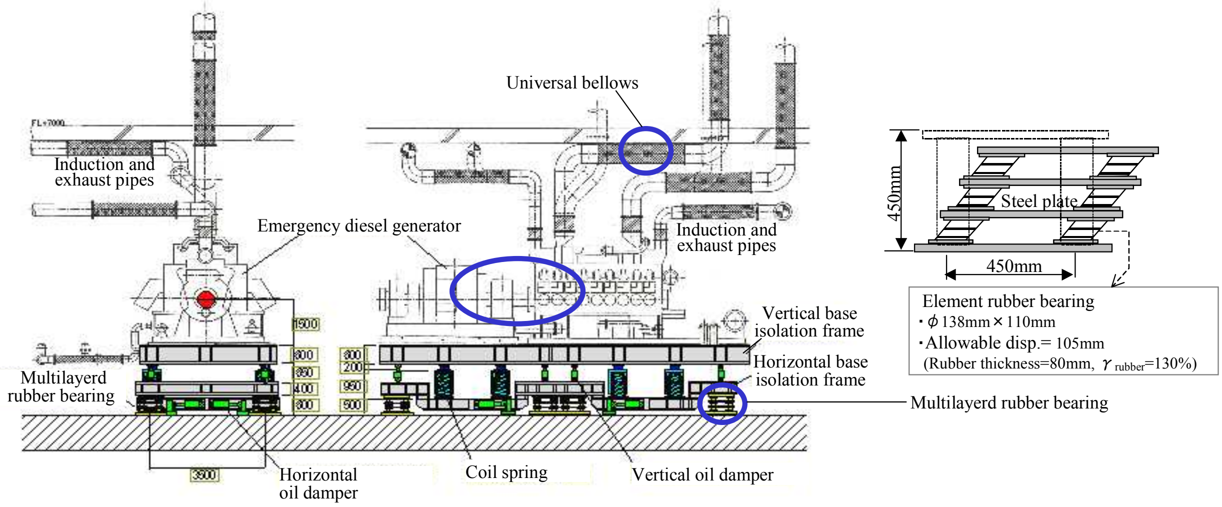


Fig. 3 Base isolation system of emergency diesel generator

(2) Multi-layer laminated rubber bearing

Each unit of multi-layer laminated rubber bearing has multiple layers and each of these layers is composed of four small pieces of laminated rubber (called “laminated rubber elements”) joined by a stabilizer plate. The number of layers is adjusted to obtain the desired natural frequency of the seismic isolation system. As major advantages of this design, the

(3) Coil springs

Coil springs are used as vertical isolation devices. The natural frequency in the vertical direction is 2Hz and the springs are assumed to have the effective stroke of +/-40mm.

(4) Oil dampers

While dampers of various designs can be used in a seismic isolation system, oil damper, whose damping characteristics is linear with response velocity, is selected in horizontal and vertical direction. The damping coefficient is 20% in the horizontal direction and 30% in the vertical direction. The maximum allowable displacement is +/-200mm in the horizontal direction and +/-40mm in the vertical direction.

(5) Intake/exhaust piping and universal bellows

The intake/exhaust piping has a bore diameter in the range between 200mm and 600mm. The connection of such large bore piping is provided using universal bellows, allowing the three-dimensional absorption of relative displacement. The maximum allowable displacement of the universal bellows is +/-220mm.

3.3 Example of Fault Tree and Setting Function Limit

Fig. 4 shows a block diagram and a fault tree prepared following the procedure described in Section 2 for use in the assessment of the probability of failure of the emergency diesel generator.

and increase the acceleration response of the diesel generator, but this does not always lead immediately to the failure of the diesel generator. These devices, therefore, are excluded from the list of critical components in the context of failure probability analysis and those degradation influences on restoring force and damping characteristics are taken into account for response analysis.

Table 2 describes the failure mode and function limit for each component or device identified by the fault tree. With regards the diesel generator, the maximum function limit acceleration for the generator is assumed to be 2200Gal on the basis of test data, with the logarithmic standard deviation of 0.3. With regards the bellows for the intake/exhaust piping, the median of the maximum tolerable displacement is assumed to be +/-220mm as designed, with the logarithmic standard deviation of 0.3.

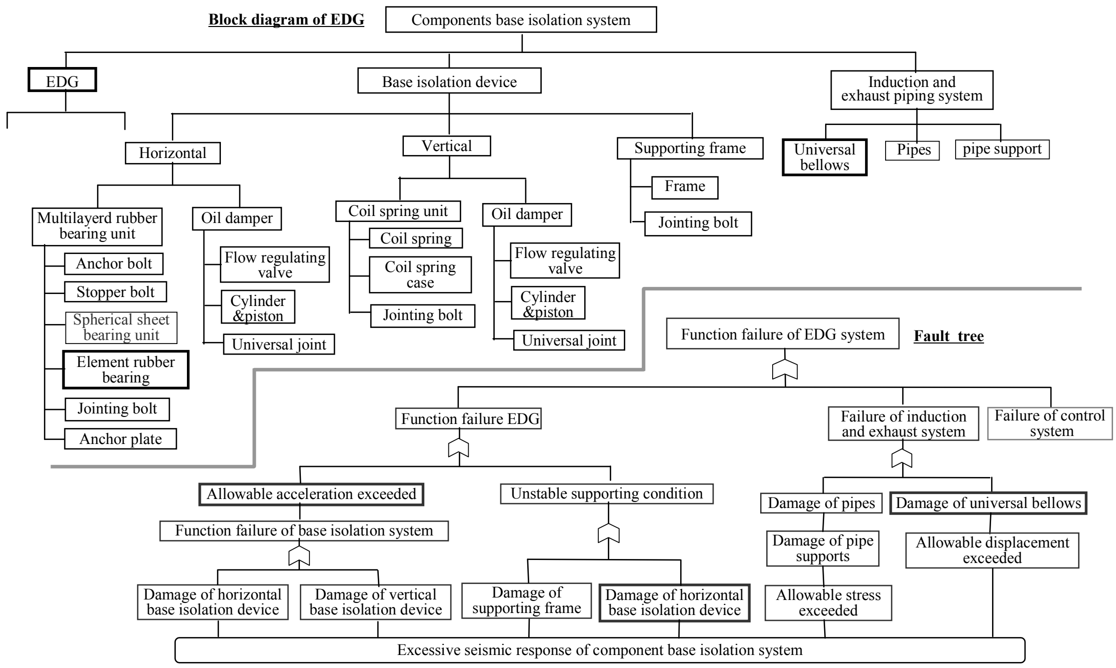


Fig. 4 Block diagram and fault tree showing failure scenarios for the base-isolated emergency diesel generator

As shown, the horizontal seismic isolation devices (multi-layer laminated rubber bearing) supporting the diesel generator and the universal bellows which is installed in intake/exhaust piping, etc. are identified as the elements whose damages are likely to lead directly to the failure of the emergency DG and as the elements require the consideration of harsh design restrictions. These devices and also the diesel generator itself are defined as critical components in the context of failure probability assessment.

As to the coil springs and oil dampers, their failures (spring getting stuck at the compressive end, oil damper going beyond the maximum allowable displacement, the failure of oil flow control valve, etc.) will spoil the seismic isolation capability

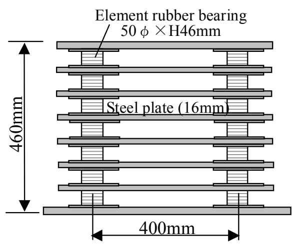
As to the multi-layer laminated rubber, the median of the maximum tolerable displacement is defined in terms of the curve of the ultimate displacement based on test data (displacement at shearing strain in the range between 100% and 200% depending on the compressive axial force), with the logarithmic standard deviation of 0.3.

4. Multi-Layer Laminated Rubber Bearing Fracture Limit Test

Laminated rubber bearing of normal design has been tested up to fracture under various loading conditions,[14)] and therefore, its fracture limit curve, showing the ultimate shearing strain at different vertical (axial) loading levels, is well defined. As to multi-layer laminated rubber bearing, however, its failure mode and fracture limit had remained unclear.

Table 2 Component base isolation device failure modes

Component and base isolation device	Failuer criterion
EDG	Acceleration, 2200Gal
Multilayerd rubber bearing	Buckling of rubber bearing , Shear strain at buckling ,100～200%
Coil spring	Allowable displacemnt,±44mm (design value)
Horizontal oil damper	Allowable displacemnt ±200mm (design value)
Vertical oil damper	Allowable displacemnt,±40mm (design value)
Universal bellows	Allowable displacemnt,±220mm (design value)



Specification of element rubber bearing

Horizontal stiffness	40±20%kgf/cm
Design vertical load	0.75tf
Thickness of rubber	0.9mm×30 layers
Thickness of inner plate	0.3mm×29 layers
Thickness of flange plate	5.0mm
1st aspect ratio	13.9
2nd aspect ratio	1.85

Fig. 5 Multi-layered rubber bearing test conditions

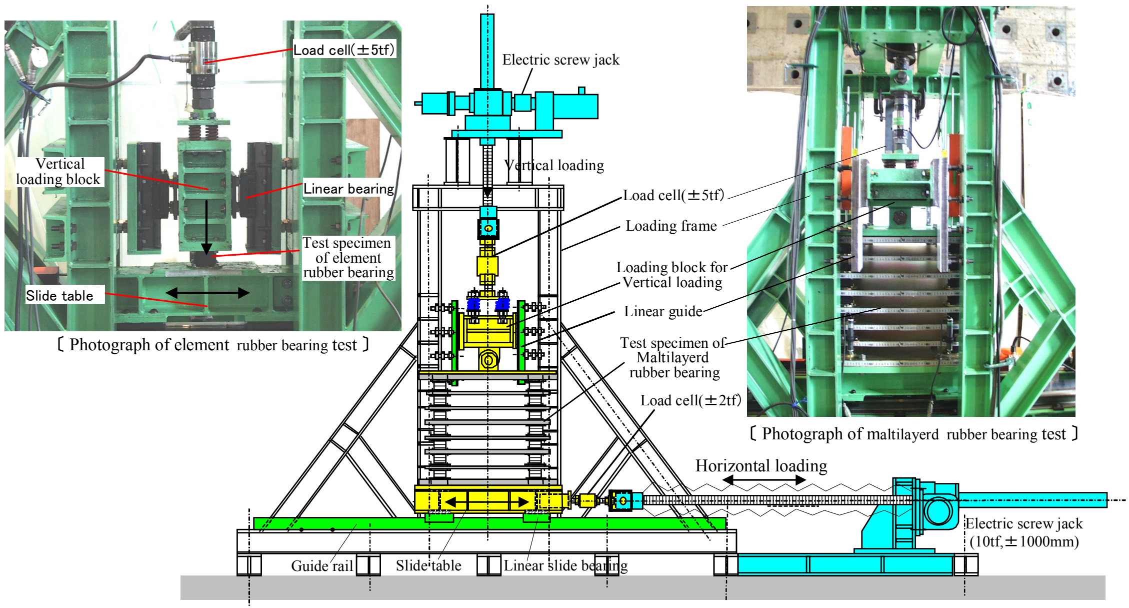


Fig. 6 Multi-layered rubber bearing loading test method

Therefore, the authors performed the testing of multi-layer laminated rubber bearings and laminated rubber elements, applying a shearing load to the specimens in the presence of an axial (vertical) load in order to clarify their failure mode and critical performance. The following describes the test process and the results.

4.1 Test Equipment and Procedure

The failure limit for a multi-layer laminated rubber bearing is determined by the point at which a failure (fracture or buckling) occurs to one or more of its laminated rubber elements, provided that the space between the laminated rubber elements is sufficiently large relative to the height and the stabilizer plates are sufficiently rigid. Compared with the laminated rubber bearing of normal design, the small laminated rubber elements are given a higher value of the secondary coefficient of shape for getting reduced stiffness in the horizontal direction. Therefore, under a great compressive pressure, they are expected to buckle before any fracture can occur.

In this test, sharing load was added to the specimens of laminated rubber element in the presence of an axial (vertical) load, which was controlled as a parameter. The ultimate displacement was measured at different loading levels to enable the determination of the fracture limit curve. In addition, a set of multi-layer laminated rubber bearing was tested under the design basis vertical load to compare with the results of the test mentioned above. Fig. 5 shows the geometry, dimensions and specifications of the multi-layer laminated rubber bearing for the testing.

Fig. 6 shows the test equipment with photographs taken during the test. The multi-layer laminated rubber bearing we tested was assumed for use in the component base isolation system for a medium size plant component weighing about 15tf, designing the vertical load of 4tf per bearing. Among ready-made products of small laminated rubber pieces, the ones that would be suitable for such application were chosen as the laminated rubber elements. The test procedure is as follows. With the vertical load kept at the chosen level during each session (but varied from session to session in the range between tensile loading and compressive loading of about twice the design basis load) and the with specimen held firmly at the top restricting its movement in the horizontal direction, a horizontal load (push/pull) was applied to the bottom of the specimen using a jack until fracture or bucking occurred. The horizontal load and displacement were measured throughout the loading operation.

4.2 Fracture Limit Test Results

Fig. 7 shows the horizontal load-displacement curve from the testing of laminated rubber element at the design basis vertical load along with a photograph of deformation. Fig. 8 is a damage limit curve showing the ultimate displacement (given in terms of shearing strain to laminated rubber) at different vertical loading levels. The failure mode and the ultimate displacement of laminated rubber element changed with the vertical load. In the presence of tensile load or minor compressive load in the vertical direction, the rubber fractured at the shearing strain of 500% to 600%. In the presence of a greater compressive load in the vertical direction, the laminated rubber element buckled before any fracture could occur. Under the design basis vertical load, bucking occurred at the shearing strain of 150%, a level at which the effective cross sectional area against the vertical load is virtually lost. Under the vertical load approximately twice as large as the design basis level, buckling occurred at the shearing strain of around 100%. The horizontal load-displacement curve shows the tendency of the stiffness decreasing gradually with the increase of deformation. As to the result of testing of a complete multi-layer laminated rubber bearing, the buckling occurred at a degree of deformation less than the ultimate deformation for the laminated rubber elements when tested under the design basis vertical load due to general bending of the entire structure. However, if the width of the multi-layer laminated rubber bearing is made sufficiently large relative to the height and the stabilizer plates are made more rigid, the failure limit for the multi-layer laminated rubber bearing is expected to be close to the ultimate displacement for the laminated rubber elements.

The results described above demonstrate the need to give attention to the interrelationship between the horizontal (shearing) and the vertical (axial) load in the failure probability assessment. In this example, as shown in Fig. 8, the most likely value of response as per the failure limit curve is determined by the evaluation of the horizontal displacement of the laminated rubber bearing and the response to vertical load (i.e. vertical load from the vertical motions, overturning moment and the eccentricity moment from the shifting of the center of gravity), and the corresponding value of the ultimate displacement is referred to in the failure probability assessment.

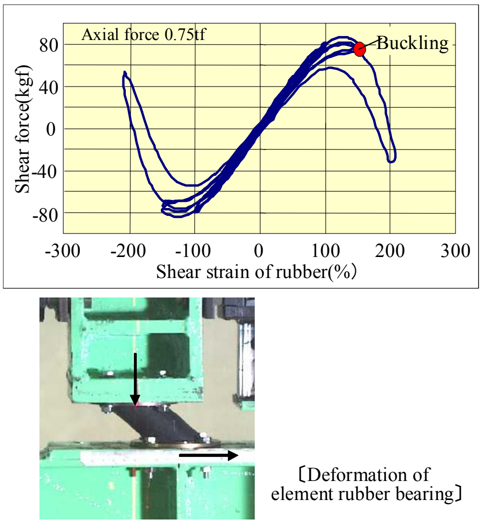


Fig.7 Load-displacement relationship of element rubber bearing under compressive load

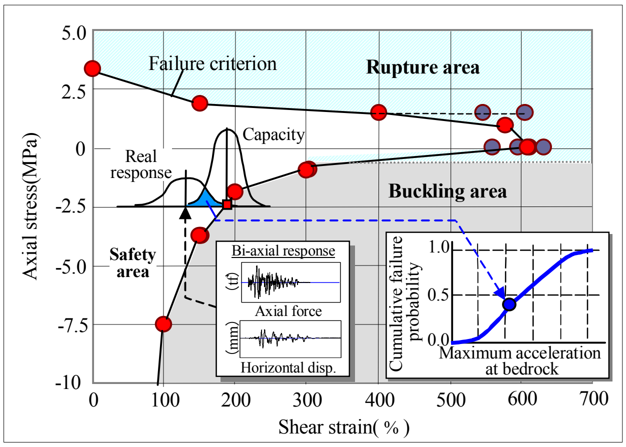


Fig.8 Failure criterion of multilayerd rubber bearing

5. Assessment of the Failure Probability of the Seismic Isolated Emergency DG and Reduction of the Failure Probability

We analyzed the seismic response of the seismic isolated emergency DG system described above (having the natural frequency of 0.4Hz in the horizontal direction and 2Hz in the vertical direction) and estimated its failure probability, paying attention to the critical components identified by the fault tree and referring to the values of function limits. Moreover, studying the assessment results with attention to the elements or devices that contribute greatly to the failure probability, we aimed at decreasing the failure probability by readjusting the characteristics of the seismic isolation system.

The type of the multi-layer laminated rubber bearing differs between this design example and the test described above. However, the two types of multi-layer laminated rubber bearing are assumed to have similar dynamic characteristics because the secondary coefficient of shape and material, of their laminated rubber elements are almost the same. Therefore, the restoring force characteristics at different levels of shearing strain and the failure limits were defined using the test data.

5.1 Analysis of the Seismic Response of the Seismic Isolated Emergency DG System

Fig. 9 shows the vibration and restoring force models of the three-dimensionally seismic isolated emergency DG system. The restoring force of multi-layer laminated rubber bearing is represented by a tri-linear characteristics model derived from the test data described above. The functioning of coil spring is represented using a bi-linear model, which assumed a sharp increase of stiffness after the ultimate displacement. As the input, to the base of the emergency DG, we used the improved standard waveform S_1F as per Fig. 10 (having the maximum horizontal acceleration of 282Gal and the maximum vertical acceleration that is a half of the maximum horizontal acceleration), adjusting it to seven levels of the maximum acceleration: 200Gal, 350Gal, 500Gal, 650Gal, 800Gal, 900Gal and 1000Gal. Assuming the input of each level, we performed the analysis of nonlinear responses using the vibration models mentioned above.

Table 3 lists the maximum response acceleration of the DG with and without seismic isolation in the horizontal and vertical directions at different levels of the maximum input acceleration. Listed in this table are the maximum response values that are relevant to the failure modes of the critical components identified by the fault tree (i.e. DG, horizontal isolation devices and intake/exhaust piping connecting bellows). The displacement at the intake/exhaust piping connecting bellows is obtained including the displacement caused by rocking motion in addition to the horizontal displacement of the seismic isolated base for the DG.

The seismic response of non-isolated DG is derived from the acceleration response spectrum at the input seismic wave frequency of 20Hz (1% damping), as shown in Fig. 10. It is assumed that the response values shown in the table are median of real responses given by Expression (4). About these values, the logarithmic standard deviation is assumed to be 0.54 based on the result of response factor analysis performed using the response factor method.[15)]

5.2 Assessment of the Failure Probability of the Seismic Isolated DG

(1) Procedure and results of the failure probability assessment

We performed the failure probability assessment assuming the seismic input of seven levels and comparing the maximum function limit with the maximum response values mentioned above for different parts of the seismic isolated DG system. The ultimate displacement for the multi-layer laminated rubber was defined as +/-320mm (130% shearing strain to the laminated rubber) from the fracture limit curve presented in Section 4, given the estimated value of vertical load. Each maximum response value was calculated as the Square Root of the Sum of the Squires (SRSS) of the responses in the two horizontal directions (these were assumed to be equal) and response in the vertical direction. The probability of failure of the seismic isolated DG system was determined in consideration of the probabilities of failure of the DG itself, horizontal seismic isolation device and the universal bellows of the intake/exhaust piping.

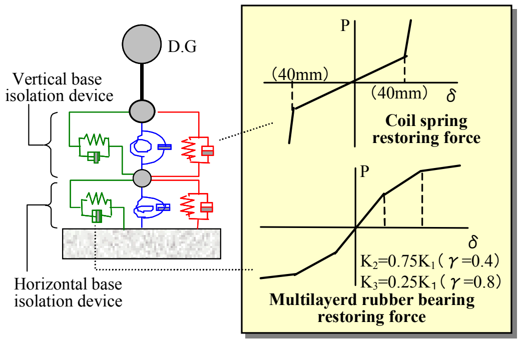


Fig. 9 Seismic response analysis model of DG with base isolation

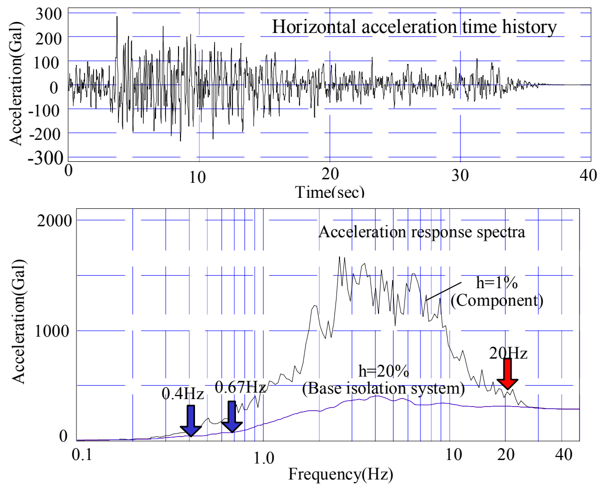


Fig. 10 Input seismic wave (S1F)

Table 3 Seismic response of DG with and without base isolation (Natural frequency=0.4Hz)

Maximum input acceleration (Gal)	Maximum acceleration of non isolation DG (Gal)			Maximum acceleration of base isolation DG (Gal)			Muximum displacement of base isolation (mm)		Rocking of vertical base isolation	Maximum displacement of universal bellows (mm)
	Horizontal	Vertical	SSRS	Horizontal	Vertical	SSRS	Horizontal	Vertical		
200	292.5	146.3	438.8	30.3	92.1	101.6	35.7	5.21	8.696E-04	39.6
350	511.9	256.0	767.9	65.2	160.4	185.0	52.8	9.08	1.516E-03	59.6
500	731.3	365.6	1096.9	75.7	228.8	252.6	89.5	12.9	2.174E-03	99.3
650	950.7	475.3	1426.0	97.1	299.9	329.8	116.2	17.0	2.782E-03	128.7
800	1170.1	585.0	1755.1	116.1	368.2	403.1	150.0	20.9	3.333E-03	165.0
900	1316.3	658.2	1974.5	129.0	412.9	451.4	162.4	23.3	3.696E-03	179.0
1000	1462.6	731.3	2193.9	141.9	460.3	502.1	180.9	26.0	4.062E-03	199.2

Fig. 11 shows the failure probability assessment results for the emergency DG with and without seismic isolation. The results show that the seismic isolation of the DG greatly reduces the probability of failure of the DG itself thanks to the availability of seismic isolating capability. However, since the bellows of intake/exhaust piping have a high probability of failure, the probability of failure of the emergency DG system with seismic isolation ($DG_{with0.4}$) is similar to the probability of failure of the emergency DG system without seismic isolation ($DG_{without}$).

(2) Reducing the failure probability by readjusting the vibration characteristics of the seismic isolation system

The assessment results indicate that the lowering failure probability of the entire system require the lowering failure probability of the piping connection. However, the increase of the allowable displacement of the universal bellows is not an easily solution because of additional space requirement. The distribution of failure probability shows that, among the three categories of critical components in this example [the DG itself, horizontal isolation devices and universal bellows], the failure probability of the DG is more than 10 times smaller than the that of the others. This suggests that a slight increase in the response acceleration of the DG will hardly increase the failure probability of the entire system. Therefore, by increasing the natural frequency of the seismic isolation system for the reduction of response displacement and by taking a measure of rocking prevention, it would be possible to reduce the failure probability of the intake/exhaust piping connection and also of the multi-layer laminated rubber bearing, which shares the same failure mode.

Table 4 shows the response of the DG after the natural frequency of the seismic isolation system is increased from 0.4Hz (natural period of 2.5 seconds) to 0.67Hz (natural period of 1.5 seconds). Fig. 12 shows the failure probability assessment results. As a result of the natural frequency having been increased, the acceleration response and failure probability of the DG slightly increase. However, the response displacement of universal bellows has decreased to about 60% of the earlier level of displacement with the natural frequency of 0.4Hz. As a result, the failure probability of the entire system with seismic isolation ($DG_{with0.67}$) is reduced to about 1/3 of the failure probability of the entire system without seismic isolation ($DG_{without}$).

(3) Failure probability assessment considering correlation of responses

In the example of assessment above, the physical quantity related to the function limit of the intake/exhaust piping connecting bellows and the multi-layer laminated rubber bearings are both defined in terms of displacement, and moreover, the displacement of the intake/exhaust piping connecting bellows highly correlates with the displacement of the multi-layer laminated rubber bearings. When there are two components that may fail, the normal practice is to refer to the failure probability of one of the two. However, if their responses highly correlate, the probability of the simultaneous failure of the two (∩ parts) becomes greater. Thus, the actual failure probability of the entire system becomes lower than the probability calculated assuming complete independence of each component. Therefore, researches should be made for the development of a methodology that enables the consideration of such correlation among responses. One of the authors has already attempted the consideration of such correlation when calculating the failure probability of plant components without seismic isolation.[2)] Learning from such attempts, it is will be necessary to consider the correlation among responses when calculating the failure probability of plant components with seismic isolation.

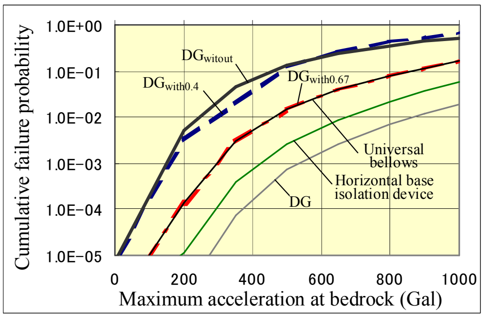


Fig.11 Failure probability of DG without and with base isolation (0.4 Hz)

Table 4 Response of the base isolated DG (natural oscillation frequency: 0.67Hz)

Maximum input acceleration (Gal)	Maximum acceleration of base isolation DG (Gal)			Muximum displacement of base isolation & universal bellows (mm)	
	Horizontal	Vertical	SSRS	Horizontal	Vertical
200	51.7	92.1	117.6	22.5	5.2
350	90.2	160.4	204.9	39.2	9.1
500	130.3	228.8	293.8	56.0	12.9
650	169.7	299.9	384.1	72.4	17.0
800	210.0	368.2	473.0	89.3	20.9
900	236.4	412.9	531.3	104.2	23.3
1000	262.1	460.3	591.0	118.0	26.0

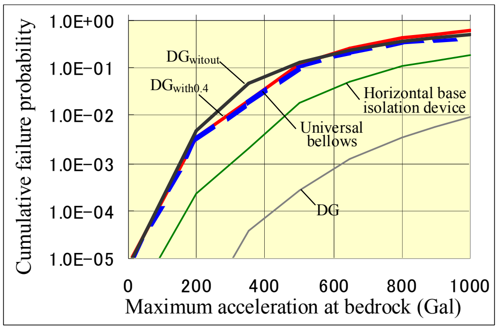


Fig.12 Probability of failure of DG with and without base isolation after changing the natural oscillation frequency to 0.67Hz (oscillation period of 1.5 seconds)

6. Conclusion and Future Challenges

(1) Conclusion

As a method for the designing of a component base isolation system and for the evaluation of its effectiveness based on the technique of probabilistic safety assessment (PSA), the paper proposed a method characterized by the use of a fault tree of the entire seismic isolation system to facilitate the identification of elements that contribute greatly to the failure probability and the accurate determination of the failure probability by means of fault tree analysis.

This paper contains an example of three-dimensionally seismic isolated emergency DG system and shows how the proposed method can be used for the assessment of the failure probability of this system. This paper also presents a failure limit curve of the multi-layer laminated rubber bearing for horizontal isolation devices determined by a two-dimensional loading test in which shearing load (horizontal) was applied in the presence of axial load (vertical). The authors have described an evaluation method of failure probability using the failure limit curve.

In this example, the assessment based on the fault tree to determine the failure probability of each critical component indicated the need to give attention to the intake/exhaust piping connection bellows because they were found to have the greatest contribution to the failure probability. The authors demonstrate how lowering the failure probability of the bellows by the readjustment of the vibration characteristics of the seismic isolation system would reduce the failure probability of the entire system.

(2) Future challenges

With the aim of reducing the frequency of core damage accident, which characterizes the severest of nuclear accidents, the authors have proposed a method based on the technique of seismic PSA for the designing of component base isolation and for the evaluation of its effectiveness.[10)] The method presented in this paper is intended for use in the assessment of the failure probability of seismic isolation devices and components important to safety. For further advancement of the assessment method, it is necessary to research evaluation method of the failure probability considering the correlation among responses.

References:

1) Risk Assessment & Analysis Laboratory; Report on Earthquake PSA for Model LWR Plants [in Japanese], JAERI-Research 99-035, 1999
2) K. Ebisawa and T. Uga: Evaluation methodology for seismic base isolation of nuclear equipment、Nuclear Engineering and Design、Vol.142、1993.
2) K. Ebisawa: Method for the Evaluating the Effectiveness of Component Base Isolation and Evaluation Code EBISA [in Japanese], RIST News No. 20, 1994
4) K. Ebisawa, et al.: Influence of various parameters on effectiveness of seismic base isolation of nuclear equipment、Transactions of The 14th International Conference on Structural Mechanics in Reactor Technology(SMiRT13)、KB08、Brazil、1995.
5) K. Ebisawa: Method for the Evaluating the Economic Efficiency of Component Base Isolation with Application Examples [in Japanese], JCOSSAR '95, 1995
6) K. Ebisawa, et al.: Progress of a research program on seismic base isolation of nuclear components、Nuclear Engineering and Design、Vol.198、2000.
7) H. Tsutsumi, et al.: Dynamic Response of Base Isolation Test System for Nuclear Component under Natural Seismic Motion、Presented at the 2000 ASME Pressure Vessels and Piping Conference, PVP - Vol. 402-1 Seismic Engineering-2000- Vol.1、、Seattle、2000
8) H. Tsutsumi, et al.: Dynamic Characteristics and Seismic Isolation Capability of Three-Dimensional Component Base Isolation System [in Japanese], the Second Colloquium on Seismic Isolation and Vibration Control, November 2000
9) Nuclear Safety Commission: Interim Report of Investigation and Discussion on Safety Goals, Special Committee on Safety Goals of the Nuclear Safety Commission of Japan [in Japanese], December 2003
10) H, Tsutsumi, et al: Research and Development of a Methodology for the Evaluation of the Probability of Failure of Seismic Isolation System for Nuclear Components [in Japanese], JCOSSAR Compilation of Papers 2003 Vol. 5, pp. 829-836, 2003
11) R.P. Kennedy,: Probabilistic Seismic Safety Study of an Existing Nuclear Power Plant、Nuclear Engineering and Design, 1980.
12) G. E. Cummings: Summary Report on the Seismic Safety Margins Research program, NUREG/ CR-4431, 1986.
13) T. Fujita, et al: Experimental Research on Multi-Layer Laminated Rubber for Seismic Isolation and Vibration Proof Floor Systems [in Japanese], Compilation of Papers by Japan Society of Mechanical Engineers, Vo.1 53, Issue 490
14) T. Fujita, et al: Experimental Research on Laminated Rubber for the Seismic Isolation of Building (Report 1: Fracture Testing of Laminated Rubber Designed to Support the Load of 100t) [in Japanese], Compilation of Papers by Japan Society of Mechanical Engineers, Vo.1 54, Issue 485
15) K. Ebisawa, et al: Method for Evaluating Real Seismic Responses of Buildings and Components [in Japanese], JAERI-Research 96-059, 1996

The figures, tables and texts of "JAERI-Tech 2001-033, Shaking Table Test and Dynamic Response Analysis of 3-D Component Base Isolation System Using Multi-layer Rubber Bearings and Coil Springs," and "JAERI-Tech 2000-086, Characteristics and Dynamic Response Analysis of 3-D Component Base Isolation System Using Ball Bearings and Air Springs" are abstracted in this chapter.

2. Three-Dimensional Equipment Isolation System

2.1 Introduction

The studies on equipment isolation carried out by the Japan Atomic Energy Agency were divided into two phases: Phase I studies and Phase II studies were carried out between 1991 and 1995 and between 1996 and 2000 respectively. In Phase I studies, (1) the probabilistic assessment method to evaluate the effectiveness of seismic isolated components was proposed, (2) the prototype of the Equipment Base Isolation System Analysis (EBISA) code was developed, and (3) effectiveness and economic efficiency of the seismic isolated start-up transformer with porcelain bushing was assessed. Furthermore, in Phase II studies, (1) the equipment isolation capability assessment using natural seismic motions and a shaking table, (2) further advancement of the EBISA code based on the test results, and (3) assessment of the effects of reducing seismic risk with the use of equipment isolation were performed.

Concerning the equipment isolation capability assessment, the "ball-bearing and air-spring type" and also the "multi-layer laminated rubber and coil-spring type" 3-D equipment isolation systems with different characteristics, mocking the nuclear equipment were designed and manufactured in 1998, and characteristic tests including the static load application test and the free vibration test were performed. The ball-bearing and air-spring type 3-D equipment isolation system has been installed on the test bed in Oarai laboratory, and seismic response has been analyzed under the natural seismic motions. Valid data to confirm the effectiveness of seismic isolation have already been obtained. The multi-layer laminated rubber and coil-spring type 3-D equipment isolation system has also been verified for seismic isolation and 3-D coupled behavior by conducting the shaking table test (during the 1999 – 2000 program).

In this report, the characteristic test results, observation results of response to natural seismic motions, analysis results of seismic response using the vibration model manufactured based on the above results, and the effects of variability in friction property of ball bearings and air springs on the seismic response were verified, regarding the ball-bearing and air-spring type 3-D equipment isolation system and the 2-D equipment isolation system (using ball-bearing) manufactured for comparison.

2.2 Ball Bearing and Air Spring Type 3-D Equipment Isolation System

2.2.1 Design and Structure of the Seismic Isolation System

(1) Design specifications

1) Setting of the natural frequencies of the seismic isolation system

Generally, the smaller the natural frequency is set, the greater the seismic isolation capability becomes. But in the meantime, displacement also increases. In the case of the equipment isolation, it is necessary to restrict displacement, considering the complexities in designing interactions or interferences with nearby components such as piping and space for installation. Although it also depends on the frequency characteristics of the input ground motion, it is considered appropriate to set the natural period of the horizontal seismic isolation at approximately 2.0 to 3.0 seconds considering the acceleration reduction effect and the amount of displacement.

Concerning vertical seismic isolation, the setting range of the natural frequency is considered to be limited to approximately 1Hz to 4Hz because the seismic isolation effect obtained by reducing the natural frequency and the loss of supporting force of the vertical load and the increase in rocking responses are in a trade-off relationship. According to the results of seismic response observation at Oarai laboratory using the vertical array, there is a tendency that the reported vertical acceleration of the seismic ground motion becomes dominant in the range near 4Hz to 5Hz. Moreover, in Southern Hyogo Earthquake and Chi-chi Earthquake in Taiwan, long-period components were dominant. Considering these factors, it is necessary to set the natural frequency of the seismic isolation system as low as possible.

Based on these points, in this seismic isolation system, it was decided to set the natural period in horizontal direction at 3.0 seconds (0.33Hz), and in vertical direction at 1.0 seconds, which is considered to be the lower limit of the natural frequency.

2) Design support load of the seismic isolation system

A nuclear power plant is a composite structure consisting of approximately 2 million components. These components are roughly divided into non-safety components related to operation, and safety related components serving to mitigate worsening an accident condition in time of an accident. In the seismic probabilistic safety assessment (PSA), accident sequences, systems and components important to safety are identified, and the equipment isolation is intended to be applied for these important components. Fig 4-1 shows the major components subject to seismic isolation, classified by installation locations and weights. Moreover, although the shapes and dimensions of the components vary significantly, their horizontal natural frequencies are in the range of 10Hz to 20Hz, and the vertical natural frequencies are estimated to be in the higher band.

Weight of a component is an especially important condition when choosing a seismic isolation device taking into consideration the natural frequency and the supporting method of the equipment isolation system. For the components more than 100tf, rubber bearing which is the most popular horizontal seismic isolation device can be applied. However, for those middle- to small-sized components whose weight is at or less than 40t, it is difficult to apply laminated rubber, as described later. As a result, there are many challenges to be overcome in the design process. Therefore, in this seismic isolation system, the weight of the component mounted on the seismic isolation device was set at

20tf assuming a middle-sized component.

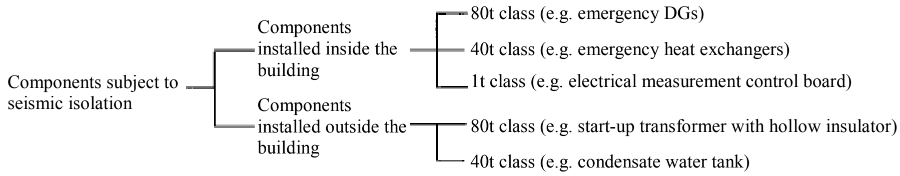


Fig. 4-1 Selection of components subject to seismic isolation[1]

(2) Structure of the 3-D seismic isolation system

1) Structure of the seismic isolation system

①rubber bearing and ②sliding bearing are considered appropriate for the horizontal seismic isolation device. Although rubber bearing is the most popular seismic isolation device, when trying to obtain required stiffness to achieve the natural period of 3 seconds by installing 4 rubber bearing units to the design load of 20tf, the ratio between the outer diameter and the rubber thickness becomes smaller and there is a risk of buckling due to small deformation. On the other hand, sliding bearing is intended for prolonging the natural period by using low friction. It has less limitation concerning weight and deformation and can be applied to light-weight component. Therefore, in this seismic isolation system, it was decided to adopt a device in which ball bearing and coil spring for adjusting the natural period.

Concerning vertical seismic isolation devices, ①coil spring and ②air spring are considered to be applicable. Although coil springs are stable, considerably large diameter and length are required for the spring if you try to obtain required stiffness to achieve the natural period of 1 second. Therefore, it was decided to adopt air springs in this system.

Fig. 4-2 shows the overview of the seismic isolation system. As is shown in the figure, this 3-D seismic isolation system consists of the following devices:

① Horizontal seismic isolation device (4 ball bearings, 4 sets of coil springs)
② Vertical seismic isolation device (4 air springs)
③ Seismic isolated base
④ Concrete block (designed assuming the weight of the middle-sized equipment)
② Seismic response observation system

In this seismic isolation system, ball bearings were installed at each corner of a square, and the seismic isolated base was supported by the bellows type air springs fixed on the ball bearings. Moreover, concrete blocks were mounted on the seismic isolated base simulating a component, and closely tied to the seismic isolated base by PC steel bars. Also, a set of 2 coil springs was installed on each side of the seismic isolated base so that the restoring force could work uniformly both positively and negatively to each direction of NS and EW.

This system was so structured that 2 viscosity dampers could be installed/removed as a damping device. Damping devices are important in restricting response acceleration and displacement which rapidly increases near the natural frequency in the seismic isolated structure. However, if you raise the damping factor too much, significant response cannot be observed as a seismic isolation device due to its resistance force in the case of medium- to small-sized earthquakes which occurs relatively frequently. In Oarai laboratory where this seismic isolation system was installed, small-sized ground motions, which were several Gals on the ground surface had been observed a dozen times per year, and larger ground motions with the size of horizontal motion of 50 – 100 Gals and the vertical motion of 20 – 50 Gals had been observed once or twice per year. Therefore, in this system, it was decided not to install viscosity dampers putting emphasis on observation of medium - to small-sized ground motions.

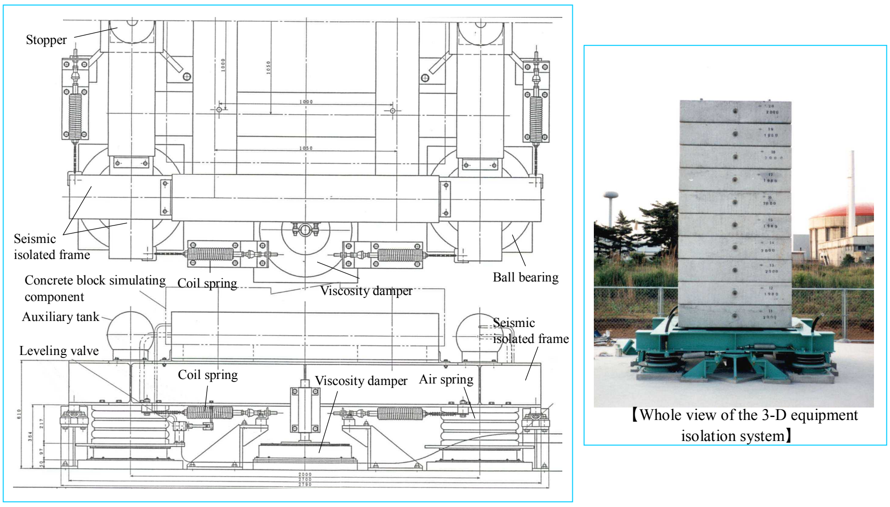


Fig. 4-2 Outline of the 3-D component base seismic isolation system[2]

2) Concrete block simulating an intended seismic isolated component

Considering adjustability of weight and easiness of manufacture, assembly and disassembly, 10 concrete block plates (height: 3.2m) were stacked to simulate component. The size of the plate was width 160cm × depth 160cm × thickness 32cm (weight: 2.0t/plate). Moreover, the ratio between the width and height of the concrete blocks was set at 1:2 so that rocking which was problem in the 3-D seismic isolation occurred prominently.

3) Ball bearing horizontal seismic isolation device

Fig. 4-3 shows the details of the horizontal seismic isolation device. The design specifications of the ball bearings and coil springs are as follows:

① Design specifications of the ball bearings

a) Design load (W) : 22tf (Weight of the simulated test specimen: 20tf, weight of the seismic isolation device: 2tf)

b) Number of bearings : 4

c) Support load per bearing : 5.5tf

d) Allowable displacement : ±100mm

e) Friction coefficient (μ) : 0.005

f) Friction force (F_d) : 110kgf (W×μ)

g) Friction damping : 7%

(μ=0.005, equivalent damping factor at free vibration with the initial displacement 100mm was calculated from the formula (2.1) based on the energy output per cycle)

[Friction damping]

$$h_e = C/\left(2\sqrt{MK}\right) = 2F_d/(\pi UK)\cdot \omega_0/\omega \qquad \cdots\cdots\cdots \quad (2.1)$$

(h e---equivalent damping factor, C---viscosity damping coefficient, M---mass, U---displacement amplitude, ω_0---natural circular frequency)

Assuming that the initial displacement is 10cm, stiffness is 98.6kg/cm (stiffness of the coil spring), friction coefficient is 0.005, the equivalent damping factor at free vibration ($\omega_0=\omega$) is calculated to be 0.07.

② Design specifications of the coil springs

a) Design load (W) : 22tf

(Weight of the simulated test specimen: 20tf, weight of the seismic isolation device: 2tf)

b) Natural period (T) :3.0 seconds

c) Horizontal stiffness (K) : 98.6kg/cm ($K = W/g \times (2\pi/T)^2$, g =980cm/sec^2)

d) Number of coil spring units : 8

(4 units in single direction, working as a set of 2 units in positive and negative sides)

e) Allowable displacement : 130mm

f) Spring constant of the coil spring : 48.8 kg/cm

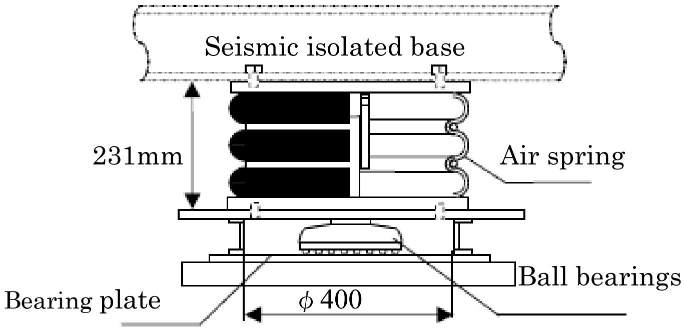
(Standard products closer to satisfying the condition of horizontal stiffness/2 units = 49.3 kg/cm were used. Stiffness was calculated by the formula (2.2).)

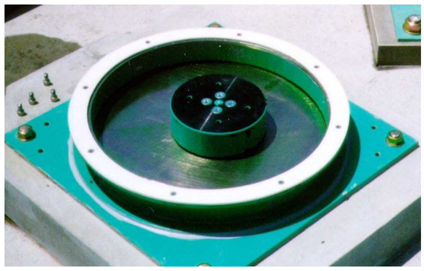
[Stiffness of the coil spring]

$$K = \frac{G \times d^4}{8 \times n \times D^3} \qquad \cdots\cdots\cdots\cdots\cdots\cdots \quad (2.2)$$

＝48.8 kg/cm (≒49.3 kg/cm)

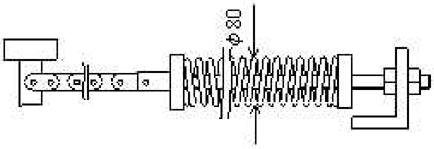
(G---modules of rigidity 8.0×10^{3}kgf/mm^2, d---wire diameter φ12mm, D---effective diameter of the coil φ68mm, n ---effective number of turns 13.5)

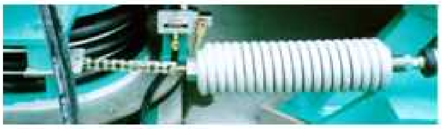




Allowable vertical load	Diameter of steel ball	Number of steel ball	Load per steel ball	Hardness of the steel ball and bearing board
6.01tf	φ22.225mm	37	162.2kg/sphere	HRc=58 (SKS93)

【a Ball bearing】





Items	Specifications
Material	SWOSM-B
Modules of rigidity <G>	8.0×10^3 kgf/mm^2
Wire diameter (d)	φ12mm
Effective diameter of the coil <D>	φ68mm
Effective number of turns <n>	13.5

【b Coil spring】

Fig. 4-3 Details of the horizontal seismic isolation device[3]

4) Air spring vertical seismic isolation device

Fig. 4-4 shows the details of the air spring. Air was supplied to the air spring from the compressor via auxiliary tank. Also, a leveling valve was attached to each air spring so that the height of the seismic isolated base was kept at the certain level. In other words, if the level became too high due to the increase of air pressure, the leveling valve was opened, and if the level became too low due to the decrease of air pressure, air was supplied from the auxiliary tank.

① Design specifications of the air springs

a) Design load : 22tf (Weight of the simulated test specimen: 20tf, weight of the seismic isolation device: 2tf)

b) Number of bearings : 4

c) Support load of the air springs (F) : 5.5tf /spring

d) Allowable displacement : vertical displacement±30mm, rotation angle 1/75

e) Effective cross-section area of the air springs : 1260 cm^2 /spring

f) Inner pressure of the air springs : 4.36 kgf/cm^2

($P = 5500\text{kg} / 1260\ \text{cm}^2 = 4.36\ \text{kgf/cm}^2 < P_{max} = 9\text{kgf/cm}^2$)

g) Air spring constant(K) : 221.7 kgf/cm^2 (Calculated by the formula (2.3))

[Stiffness of the bellows type air springs]

$$K = \gamma(P_0 + Pa)A^2/V_0 + 0.68\pi P_0 A/(nd) \quad \cdots\cdots\cdot \quad (2.3)$$

$$= 221.7 \quad \text{kgf/cm}$$

γ : Polytropic exponent (static change=1.0, dynamic change=1.4)

P_0 : Inner pressure (Design value=4.36 kg/cm^2)

Pa : Atmospheric pressure (=1.0 kg/cm^2)

d : Effective diameter at the standard height (Design value=40cm)

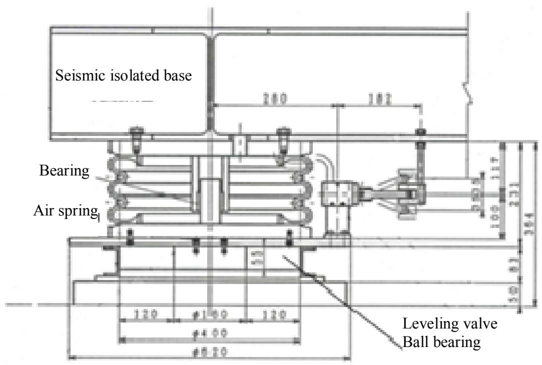
A : Effective area at the standard height (Design value=1260cm^2)

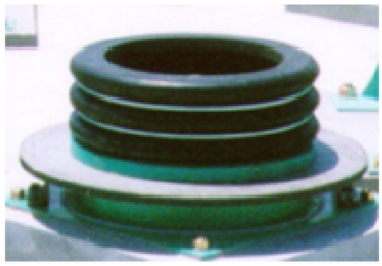
V_0 : Sum of the volume of bellows and auxiliary tank at the standard height (Design value =V+Vs=96140cm^3)

n : Folds of bellows (Design value = 3)

Therefore, natural period is as follows:

$$T = 2\pi\sqrt{F/g/K} = 2\pi\sqrt{(5500/980/221.7)} \quad = 1.0 \text{ second}$$





Design specifications	Specified values
Effective diameter (d)	400mm
Number of folds (n)	3 folds
Standard height (h)	160mm
Strokes (e)	±68mm
Effective area (A)	1260cm^2
Inner volume (V)	19500cm^2
Maximum working inner pressure (Pmax)	9.0kgf/cm^2
Volume of auxiliary tank (Vs)	76640cm^3

Fig. 4-4 Details of the vertical seismic isolation device (air spring) [4]

(3) Structure of the 3-D seismic isolation system

The 2-D seismic isolation test system was manufactured using the horizontal seismic isolation device (ball bearing) with the same specifications as the one used in the 3-D equipment isolation system in order to compare and examine the seismic isolation capabilities and dynamic behavior of the 3-D equipment isolation system. Both systems were used for observation of seismic responses under the same environment. Fig. 4-5 shows the entire structure of the 2-D seismic isolation system. As the figure shows, the 2-D seismic isolation system has the same structure as the above-mentioned 3-D seismic isolation system except the air spring, and consists as follows:

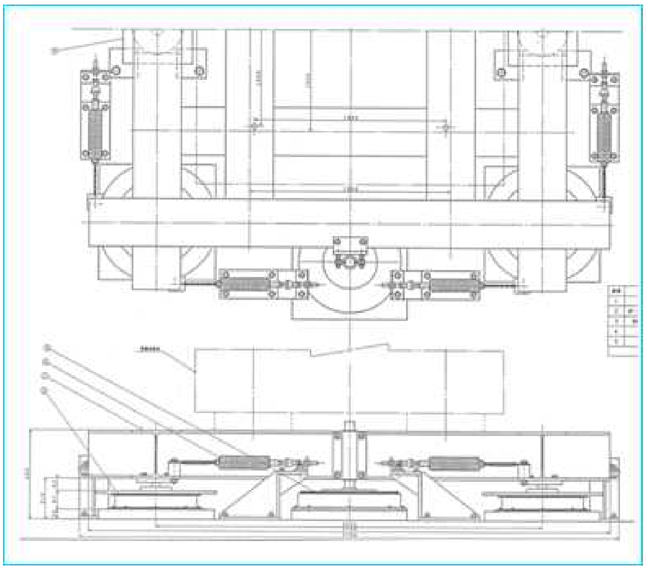
(1) Horizontal seismic isolation device (with the same specifications as the one used in the 3-D equipment isolation system)

(2) Seismic isolated base frame

(3) Concrete blocks (with the same specifications as the one used in the 3-D equipment isolation system)

(4) Seismic response observation system

In this example, the seismic isolated base frame and concrete blocks were mounted on the ball bearings.



【Whole view of the 2-D equipment isolation system】

Fig. 4-5 Outline of the 2-D component base seismic isolation system[5]

2.2.2 3-D Seismic Isolation Capability Test

(1) Horizontal static load test

Fig. 4-6 shows the horizontal static load application and measurement methods. As the figure suggests, the threaded shaft ends of the electric screw jacks (thrust force 10t ×stroke 2000mm) were fixed to both ends of the seismic isolated base frame, and forced displacement was applied alternately to negative and positive directions with 2 jacks. Same displacement was repeatedly forced 3 times in a load application cycle.

The load was measured by the load cell (capacity 2tf, resolution capability 0.7kg) mounted on the top of the jack, while the displacement was measured by applying the displacement gauge (range ±100mm, resolution capability 0.02mm) to the seismic isolation frame located opposite to the jack. The output signals from the load cell and the displacement gauge were input into the dynamic strain gauge. Continuous measurement was performed from one peak to another peak of the load application cycle at the sampling frequency of 10 – 50Hz when obtaining friction characteristics.

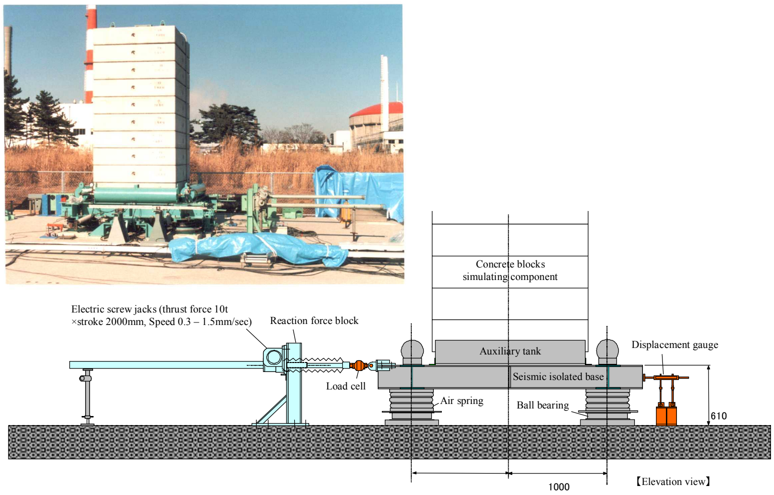


Fig. 4-6 Horizontal static load test method[6]

(2) Vertical and static rocking load test

Fig. 4-7 shows the methods of vertical and rocking load application and measurement. As the figure suggests, the jacks were vertically installed at four corners of the seismic isolated base frame, and load was applied after fixing the threaded shaft ends to the floor by pins. In the case of the vertical static load test, same displacement was applied to four jacks. In the case of the static rocking load test, displacement in the opposite directions (angle of rotation) with the same absolute values was applied to a set of 2 jacks which stood in parallel in NS and EW direction, respectively. Same displacement was repeatedly forced for 3 times in a load application cycle.

The load was measured by the load cell (capacity 2tf, resolution capability 0.7kg) mounted on the top of the jack, while the vertical displacement was measured by the displacement gauges (range ±25mm, resolution capability 0.005mm) mounted at each corner of the seismic isolated base vertically downward. The changes in inner pressure inside the auxiliary tank of each air spring were measured by the pressure inverter (capacity 10kg/cm^2, resolution capability 0.004kg/cm^2).

Each output signal of the load cell, displacement gauge and pressure inverter was input to the dynamic strain gauge, and continuously measured for the entire load application cycle at the sampling frequency of 10Hz.

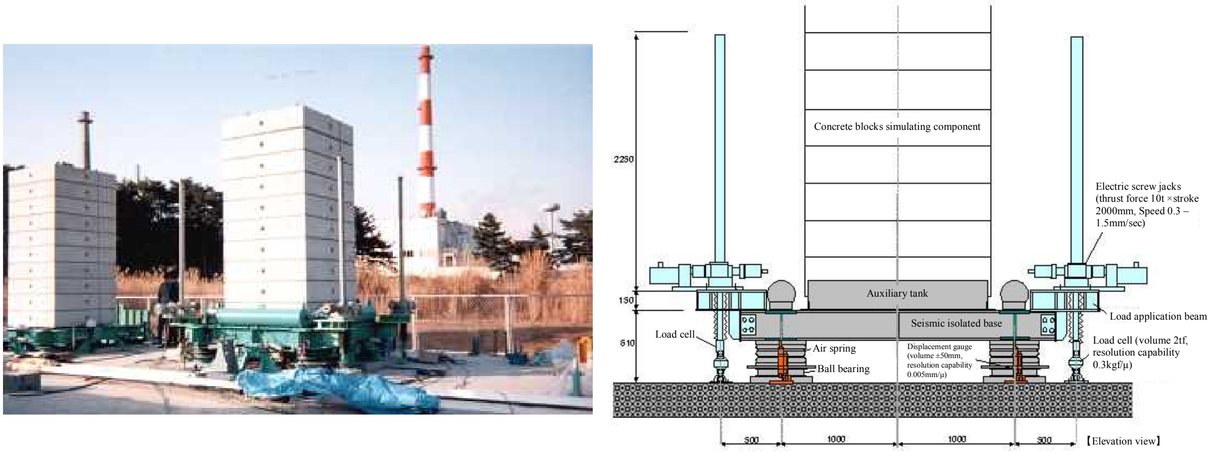


Fig. 4-7 Methods of vertical and rocking load tests[7]

(3) Horizontal free vibration test

Fig. 4-8 shows the method of generating the horizontal free vibration and the method of measuring the vibration. As the figure suggests, initial displacement was applied by drawing both ends of the seismic isolated frame with lever blocks and wires. Then, free vibration was generated by cutting the reinforcing steel inserted in the middle. The initial displacement was decided to be 90mm at the maximum.

During the free vibration, the velocity and acceleration of 3 components of NS, EW and UD at the top of the concrete blocks simulating a component (resolution capability of the speed meter 0.2Kine, resolution capability of the acceleration meter 0.2Gal), the horizontal displacement at both ends of the seismic isolated frame (displacement gauge: range ±100mm, resolution capability 0.02mm) and vertical displacement at 4 corners of the seismic isolated base (range ±25mm, resolution capability 0.005mm) and the inner pressure of the air spring were measured. The output signals from each sensor were input to the dynamic strain gauge and measured at the sampling frequency of 100Hz.

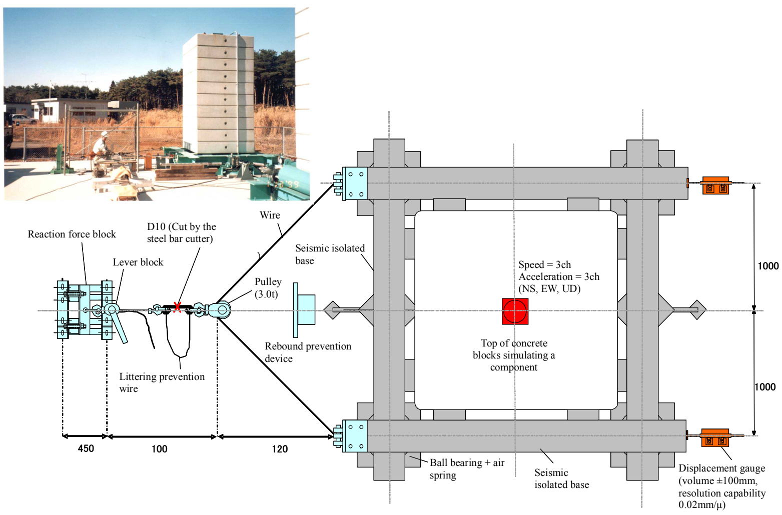


Fig. 4-8 Method of horizontal free vibration test[8]

(4) Vertical free vibration test

Fig. 4-9 shows the method of applying the vertical load and rocking and also the method of measurement. As the figure suggests, the jacks were vertically installed at four corners of the seismic isolated base, and load was applied after fixing the threaded shaft ends to the floor by pins. In the case of the vertical static load test, the same displacement was applied to four jacks. In the case of the static rocking load test, displacement in the opposite directions (rotation angle) with the same absolute values was applied to a set of 2 jacks which stood in parallel in NS and EW direction, respectively. Same displacement amplitude was repeated for 3 times in a load application cycle.

The load was measured by the load cell (volume 2tf, resolution capability 0.7kg) mounted on the top of the jack, while the vertical displacement was measured by the displacement gauges (range ±25mm, resolution capability 0.005mm) mounted at each corner of the seismic isolation base frame vertically downward. The changes in inner pressure inside the auxiliary tank of each air spring were measured by the pressure inverter (capacity 10kg/cm^2, resolution capability 0.004kg/cm^2).

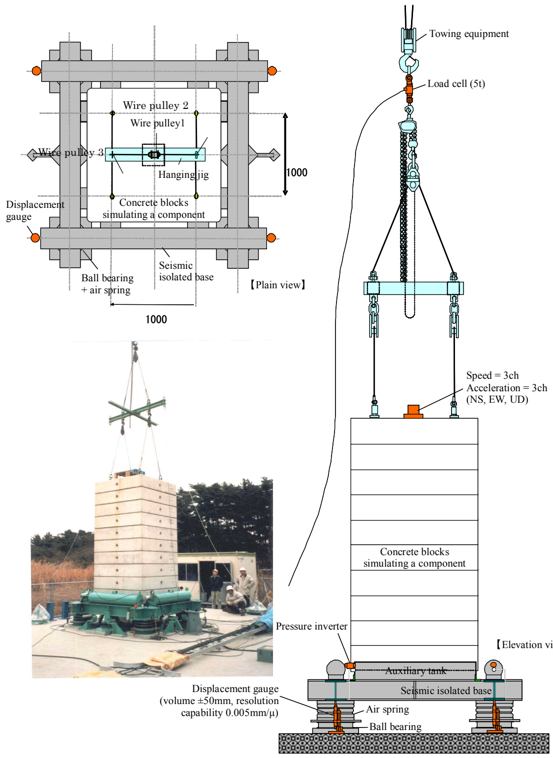


Fig. 4-9 Method of vertical free vibration test[9]

2.2.3 Results of the 3-D Seismic Isolation Performance Test

(1) Results of the horizontal static load test

1) Friction characteristics of the ball bearings

Fig. 4-10 shows the relationship between the load (total load of 2 jacks) and displacement (average of 2 displacement gauge), or the friction characteristics of the ball bearings in NS and EW directions when load was applied after removing the coil spring. Each load-displacement relationship was obtained by applying the same forced displacement for 3 cycles. However, these relations form almost the same history loop, and thus repeatability of the friction characteristics was observed. The average friction coefficient calculated from the load - displacement relation was 6.11/1000 (average of positive and negative values 134.5kg/22000kg) in NS direction, and 7.19/1000 (average of positive and negative values 158.2kg/22000kg) in EW direction, thus approximately

15% of difference occurred. Although ball bearings slide at almost constant load, and display the record characteristics to friction, the friction load is approximately 25% higher than the average in NS direction at the initial load application, and also some variation is exhibited when the load is removed. Moreover, the friction load is greater on pushing side than pulling side.

2) Characteristics of restoring force of coil springs and ball bearings

Fig. 4-11 shows the relationship between the load (total load of 2 jacks) and displacement (average of 2 displacement gauge) when the coil springs are installed in each load application direction. Each load - displacement relationship forms almost the same history loop for the repetition of the same forced displacement and thus exhibits stable and reproducible restoring force characteristics. Dashed line in the figure shows the regression formula of stiffness obtained from the load – displacement relationship.

The restoring force characteristics of the seismic isolation system shows the bilinear type history characteristics, that is, displacement amplitude is small, while stiffness is slightly high, and as the displacement increases, stiffness decreases. Although the average stiffness calculated from the load-displacement relation is 11.57kg/mm in NS direction, and 11.44kg/mm in EW direction, and thus almost the same, they are 16 – 17% higher than the design value (9.86kg/mm).

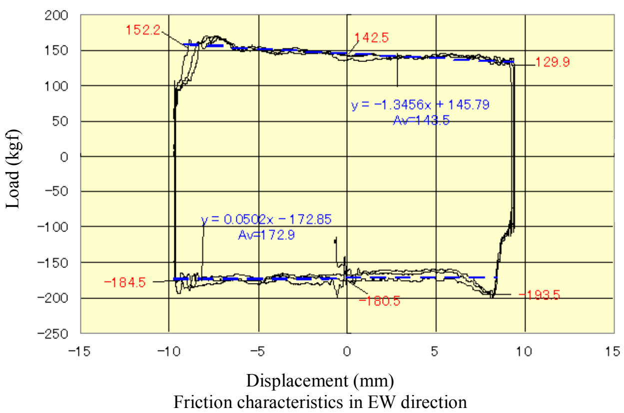


Fig. 4-10 Friction characteristics of ball bearing[10]

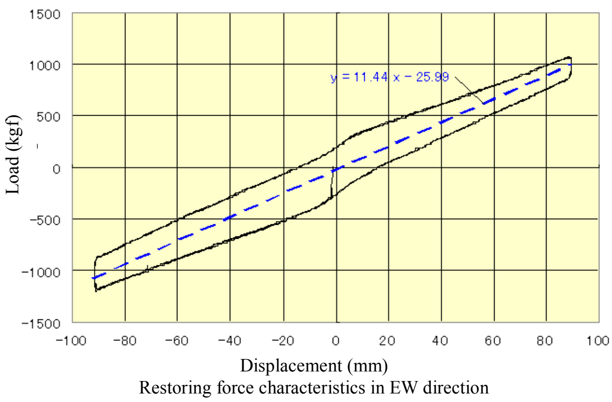


Fig. 4-11 Restoring force characteristics[11]

(2) Results of the vertical and static rocking load test

1) Restoring force in vertical direction

Fig. 4-12 shows the relationship between the total load of all the jacks and the average displacement when the same displacement amplitude of ±20mm was applied to each jack in vertical direction. This suggests the restoring force characteristics of 4 air springs in vertical direction. The load-displacement relation was obtained by repeating the application of the same displacement amplitude for 3 cycles. Each relation forms almost the same history loop, and thus exhibits stable and reproducible characteristics. Although the restoring force characteristics show a slightly bulging, oval type history loop, area is small and damping force of air springs is small. The stiffness obtained from the load-displacement relation was 95.51kg/mm, which was approximately 7% higher than the design value of 88.7kg/mm.

2) Rocking restoring force characteristics

Fig. 4-13 shows the rotation moment – rotation angle relationship when the rotation angle of ±1/100 was applied in NS and EW directions. As the positional relation between the jacks and displacement gauge shown in the same figure suggests, the rotation moment was obtained from the total load of the jacks of the same load application direction multiplied by the force application span. The rotation angle was calculated by the average difference of the relative displacement divided by the measurement span.

Although the history loop exhibits an oval loop similar to the case observed in vertical direction, the area is slightly larger. The average stiffness obtained from the history curve is 5.80×10^4 (kgfm/rad) in NS direction, and 5.67×10^4 (kgfm/rad) in EW direction, and thus it is almost the same in both directions.

Some disturbance is observed in the restoring force near the load zero area, especially in the history curve in NS direction. This is considered to be generated by the slide occurring at the loose hole at the pin bearing section, provided to prevent excessive bending moment from generating at the top of the jack in association with rotation.

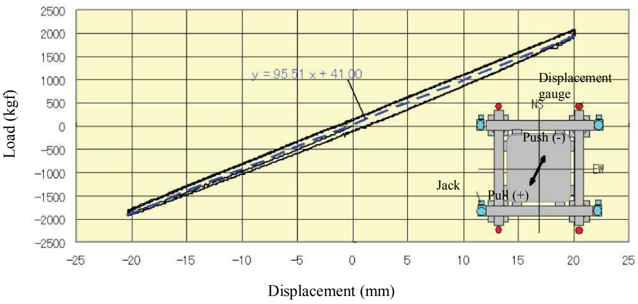


Fig. 4-12 Vertical restoring force characteristics[12]

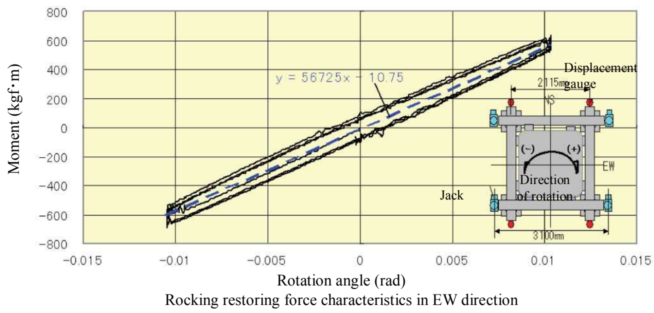


Fig. 4-13 Rocking restoring force characteristics[13]

(3) Results of horizontal free vibration test

Fig. 4-14 shows the time history of the horizontal displacement and vertical displacement in both NS and EW directions. In the time history of the horizontal displacement, oscillation of small amplitude continues due to the horizontal displacement associated with rocking, about which is explained later, because the translation mode is compensated at the initial response due to friction and rocking of the ball bearings in both directions.

On the other hand, in the time history of the vertical displacement, it can be observed that rocking is predominant from the fact that the displacement opposite to each of NS and EW direction of rotation oscillates almost in the opposite phase. However, in the free vibration test in NS direction, the period and amplitude of each vertical displacement are roughly in accordance, and rocking mostly in NS direction. On the other hand, in EW direction, the amplitudes of the displacement gauge SE and NW are small while the amplitudes of NE and SW, located at their diagonal positions, are large.

Therefore, rocking occurs also in the NE-SW direction, rotating around the diagonal between SE and NW. Probable causes of rocking to the diagonal directions are variation of the initial displacement when the forced displacement is applied (initial displacement of SE and NW is large), and the influence of the difference in inner pressure inside the air springs (pressure in the air springs located at SE and NW is higher).

The rocking period in NS direction obtained from the time history of each of the vertical displacement is 2.65 seconds in the displacement at SE and NW, and 2.70 seconds in the displacement at NE and SW, while damping factors are 5.2% and 4.7%, respectively, and thus generally consistent with each other. On the other hand, in EW direction, the displacement of SE and NW is 2.56 seconds, and that of NE and SW is 2.75 seconds, while the damping factors are 4.9% and 8.8%, respectively, which indicates that the difference of the displacement amplitude in diagonal directions effects the period and frequency.

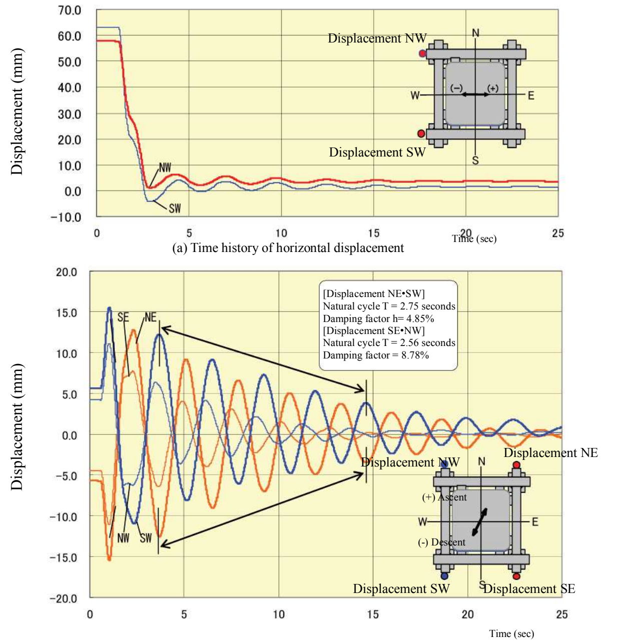


Fig. 4-14 Results of free vibration test in EW direction[14]

(4) Results of vertical free vibration test

Fig. 4-15 shows the time history of the vertical displacement at the center bottom of the concrete blocks and four corners of the seismic isolated base frame at the initial displacement of 20mm. Although there are some differences in the time history of each initial displacement measured at four corners of the seismic isolated base, it vibrates almost the same phase and same amplitude, which shows that oscillation characteristics in vertical direction can be

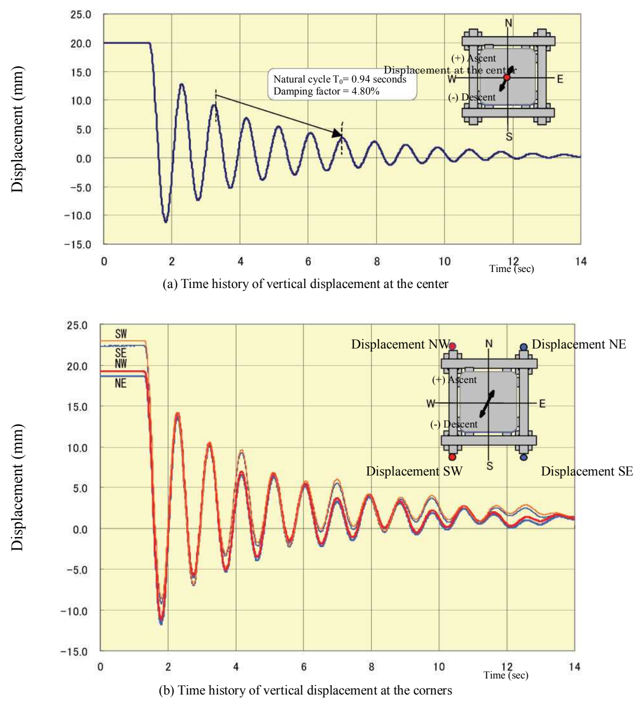


Fig. 4-15 Results of vertical free vibration test[15]

assessed by the results of this test. The period obtained from the time history of displacement at the center bottom of the concrete blocks is 0.94 seconds, while the damping factor is 4.8%, and the period mostly agrees with the design value.

2.2.4 Observation Example of Response to Natural Ground Motion

(1) Specifications and characteristics of the observed ground motion

Fig. 4-16 shows the principle data including the occurrence location, size and focal depth of the earthquakes occurring on March 26 and April 25, 1999, and the time history of acceleration, Fig. 4-16 also shows Fourier spectrum and response spectrum of acceleration observed on the test bed on which the seismic isolation system was installed. These earthquakes occurred at almost the same location and their sizes were almost the same. The characteristics of these ground motions are as follow:

○ Ground motion observed on March 26

The maximum acceleration observed on the test bed was 86.1 Gals in NS component, 58.4 Gals in EW component, and 25.1 Gals in vertical component, and the range of dominant frequency was in 5Hz - 6Hz in NS component, 2Hz - 7Hz in EW component, and 3Hz - 9Hz in vertical component.

The acceleration response spectrum was higher than that of the input acceleration in the period at equal or shorter than 0.4 seconds in NS direction, 0.6 seconds in EW direction and 0.4 seconds in vertical direction. In addition, the acceleration response spectrum decreases to below 1/10 near the range where the natural period of horizontal seismic isolation was 3.0 seconds, and to approximately 1/4 near the range where the natural period of vertical seismic isolation was 1.0.

Title of earthquake	Dates of occurrence	Site of occurrence	Magnitude	Focal depth of earthquake	Epicenter distance	Maximum acceleration (Test bed, Gal)
EQ-99326	1999-3/26-8:31	Northern part of Ibaraki prefecture	5.1	50km	20km	NS=86.1/EW=58.4/UD=25.1

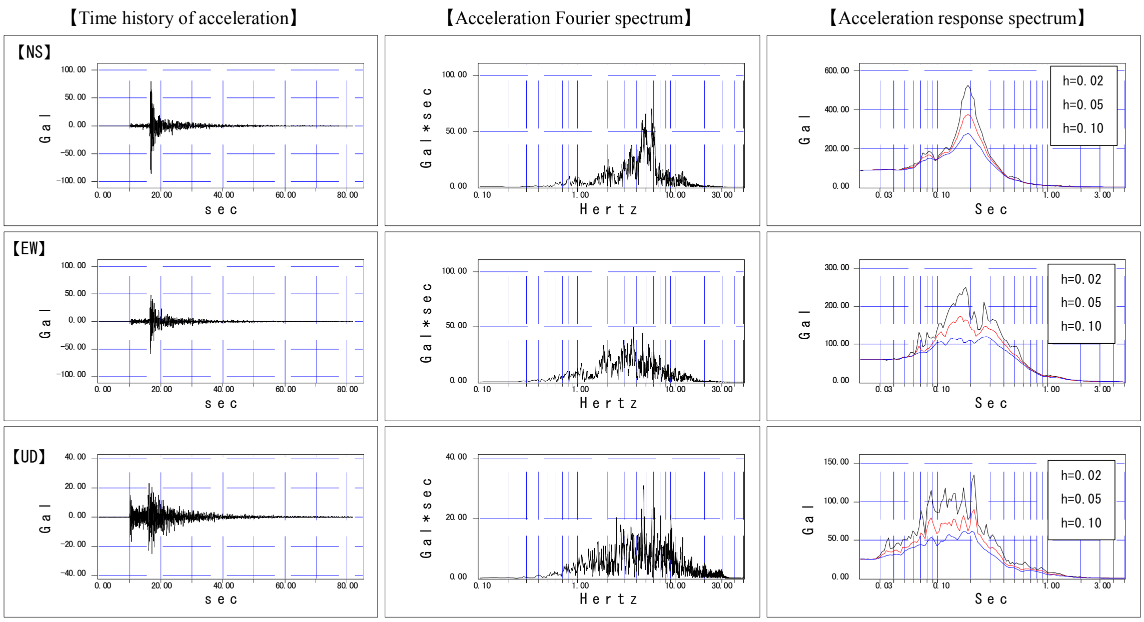


Fig. 4-16 Observed ground motion and major data[16]

(2) Results of seismic response observation

Table 4-1 shows the observation results of the 3-D seismic isolation system and the 2-D seismic isolation system concerning EQ-99326. The following is the discussion about the response characteristics of each seismic isolation system.

Fig. 4-17 (a) shows the time history of response acceleration, Fourier spectrum and transfer function to the input acceleration at 3 corners on top of the concrete blocks of the 3-D seismic isolation system. Fig. 4-17(b) shows the time history of response displacement in NS and EW directions of the seismic isolation frame, and Fourier spectrum. Fig. 4-17(c) shows the time history of the rotation angle and Fourier spectrum.

Table 4-1 List of seismic response observation results [17]

		On the test bed	3-D seismic isolation	2-D seismic isolation
Maximum input acceleration (Gal)	NS	86.06	46.37(0.54)	45.65(0.53)
	EW	58.35	38.88(0.67)	45.59(0.78)
	Vertical	25.15	9.46(0.38)	68.17(2.71)
Maximum speed (Kine)	NS	2.94	1.58	1.35
	EW	3.20	2.26	2.22
	Vertical	0.79	1.28	1.11
Maximum displacement (mm)	NS	-	1.02	1.63
	EW	-	1.28	3.73
	Vertical	-	1.91	0.03

Values in the brackets of the maximum response acceleration columns show the response amplification ratios to the input acceleration

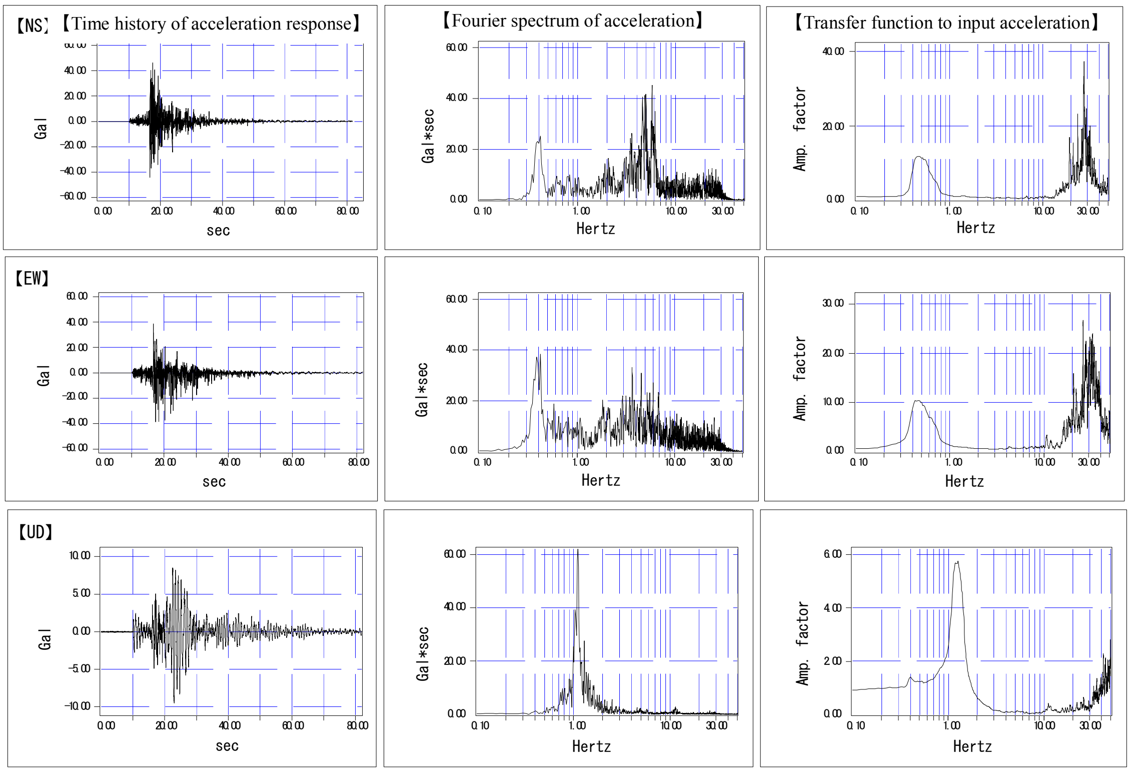


Fig. 4-17(a) Response acceleration of the 3-D component base seismic isolation system[18]

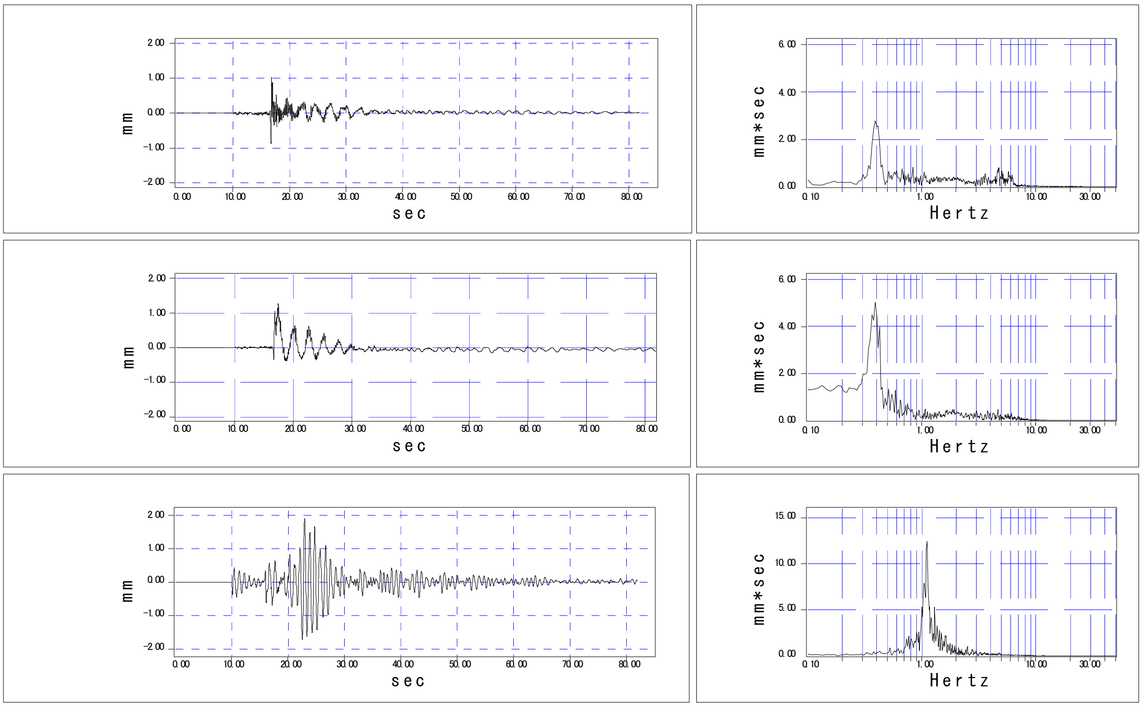


Fig. 4-17(b) Displacement response of the 3-D component base seismic isolation system[19]

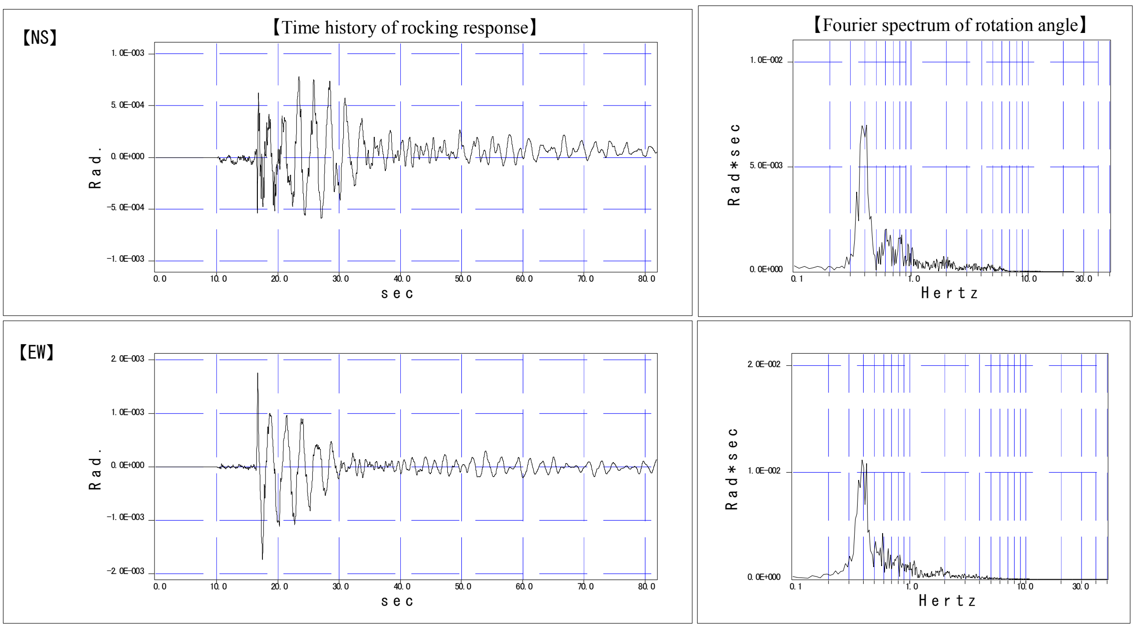


Fig. 4-17(c) Rocking response of the 3-D component base seismic isolation system[20]

2.2.5 Comparison of Seismic Response Analysis Results Based on the Vibration Model and Actual Observation Results

(1) Outline of vibration model

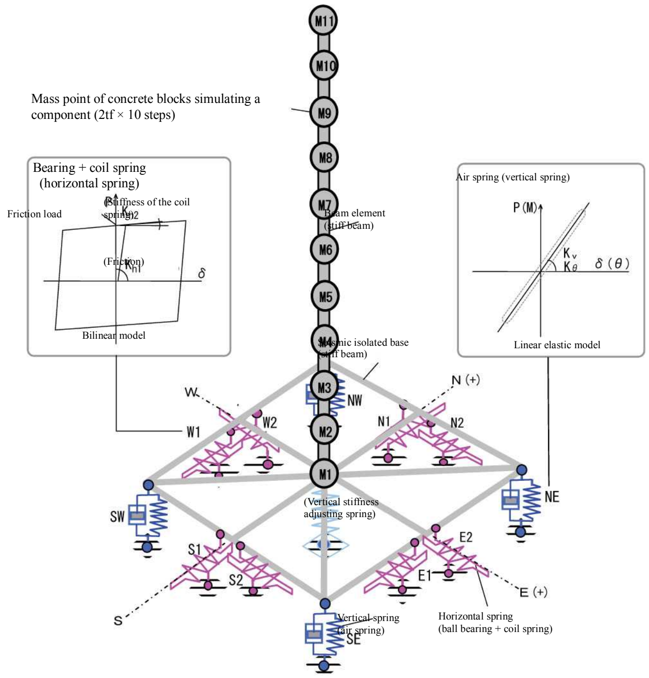
The 2-D sway rocking (SR) model is generally used in the analysis of buildings and components, and useful for designing, considering the balance among ease of use, time required for analysis and accuracy of analysis. However, in this 3-D component base seismic isolation test system, there are some factors to compound the behaviors specific to 3-D, such as occurrence of the 3-D response behavior due to rocking and variation of stiffness of air springs, as it was observed in the seismic response observation discussed in the previous section. The 2-D SR model cannot represent these 3-D specific responses.

Therefore, the 2-D vibration model (SR model) and the 3-D vibration model were developed. In the 2-D model, the elements constituting the seismic isolation system, including ball bearings, coil springs, and air springs, were separately grouped in NS and EW directions, and represented by horizontal springs, vertical springs and rotary springs. In the 3-D model, each seismic isolation element was represented by the springs, and faithfully modeled according to the component base isolation system. Then the analysis accuracy of these 2-D and 3-D vibration models was verified using the observation results of EQ-99326. The following are the outline of the models.

Fig. 4-18 shows the 3-D vibration model. As the figure suggests, ball bearings, coil springs and air springs, constituting the seismic isolation system, were replaced by respective spring elements, and properly arranged in order to faithfully represent the structure of the seismic isolation system. The restoring force model and the damping factor of each spring element were set based on the results of characteristic test and seismic response observation, in the same way as the 2-D vibration model. However, stiffness of the coil spring and air spring elements was applied as a uniform stiffness by dividing the average stiffness obtained by the characteristic test by a number of elements.

Concerning the air spring elements, if the stiffness obtained by the vertical load carrying test is applied as the stiffness of each air spring element, the rotation stiffness becomes greater than the rotation stiffness obtained by the characteristic test and the results of the seismic response observation (natural frequency of rocking response) (The stiffness of individual air spring element is decided by the relation between the vertical displacement and axial force. The stiffness never changes in the case where the axial force itself directly works, and the case where the axial force works by the moment.) Influence of eccentric moment, generated by horizontal movement of the position of the center of gravity of concrete blocks associated with rocking is considered to be a major factor causing difference between the analysis model and measurement results regarding the rotation stiffness. In other words, in the analysis, only the overturning moment caused by inertia force in horizontal direction at each mass point is considered, while in the response based on observation results, rocking increases due to the addition of the above-mentioned eccentric moment. As a result, the rotation stiffness appears to be lower than the stiffness in the analysis mode. In this 3-D seismic isolation system, influence of eccentric moment is greater because of smaller rotation stiffness, which is equivalent to approximately 33% reduction of stiffness (given this reduction of stiffness, it is almost corresponding to the rotation stiffness of the characteristic test and the observation results).

Considering these geometric non-linear effects and material’s non-linear effects simultaneously in the calculation at each time step makes algorithm and judgment of convergent calculation extremely complicated. It is impossible to directly consider these effects in the code used in this analysis. Therefore, in this analysis model, the stiffness of the air spring element installed at four corners of the seismic isolation base is set according to the rotation stiffness assessed from the characteristic test, and in the meantime spring element is added to the center of the seismic isolated base in order to adjust the vertical stiffness equivalent to the stiffness obtained by the characteristic test.



Specification of analysis model

	M1 (seismic isolated base)	M2-M11 (Concrete blocks)	Total
Weight of mass point	2.0	2.0×10 steps	22.0

Types of spring, etc.	Unit	Stiffness		Restoring force model	Damping ratio
Horizontal spring (N1, S1, E1, W1)	kgf/mm	K_{h1}=5.0*10^3	K_{h2}=2.89	Bilinear type	Damping due to friction
(N2, S2, E2, W2)	kgf/mm	K_{h1}=5.0*10^3	K_{h2}=2.86	↑	↑
Friction load (NS)	kgf	134		-	-
(EW)	kgf	158		-	-
Vertical spring (NE)	kgf/mm	14.52		Linear type	5%
(SE)	kgf/mm	14.52		↑	↑
(SW)	kgf/mm	14.52		↑	↑
(NW)	kgf/mm	14.52		↑	↑
(CL)	kgf/mm	37.41		↑	↑

Fig. 4-18 Ball bearing + air spring type, 3-D vibration model[21]

(2) Comparison of the results of seismic response analysis with observation

1) Conditions and method of analysis

Seismic response analysis was conducted using the 2-D and 3-D vibration models, assuming EQ-99326 as an input ground motion. In the 2-D analysis model, input was applied to 2 directions consisting of 1 component of horizontal 2 components (NS and EW), plus vertical component. In the 3-D model, input was simultaneously applied to 3 components. Newmark-β method (β=1/4) was used in the analysis and integral time interval was set at 1/1000 seconds.

2) Results of analysis

Table 4-2 shows the results of analysis. Fig. 4-19 (a) to (d) show the time history and the Fourier spectrum of horizontal and vertical acceleration at the top of the concrete blocks, horizontal displacement and rocking (rotation angle) of the seismic isolated base and observation results by each model. The results of analysis of the horizontal displacement of the seismic isolated base are expressed by adding the displacement obtained from offset between the measure point and the center of rotation (seismic isolated base) (NS direction = 183mm, EW direction =223mm) multiplied by the response of rotation angle, in order to match the observation results and conditions.

Table 4-2 Results of 3-D vibration model analysis [22]

Analysis model		2-D model	3-D model	Observed values
Maximum acceleration at the top of concrete blocks (Gal)	NS	33.2	55.0	46.3
	EW	29.9	36.3	38.9
	Vertical	7.50	7.50	9.46
Maximum displacement at seismic isolated base (mm)	NS	1.02	0.53	1.02
	EW	1.51	0.56	1.28
Vertical displacement at the bottom of concrete blocks (mm)		1.75	1.75	1.91

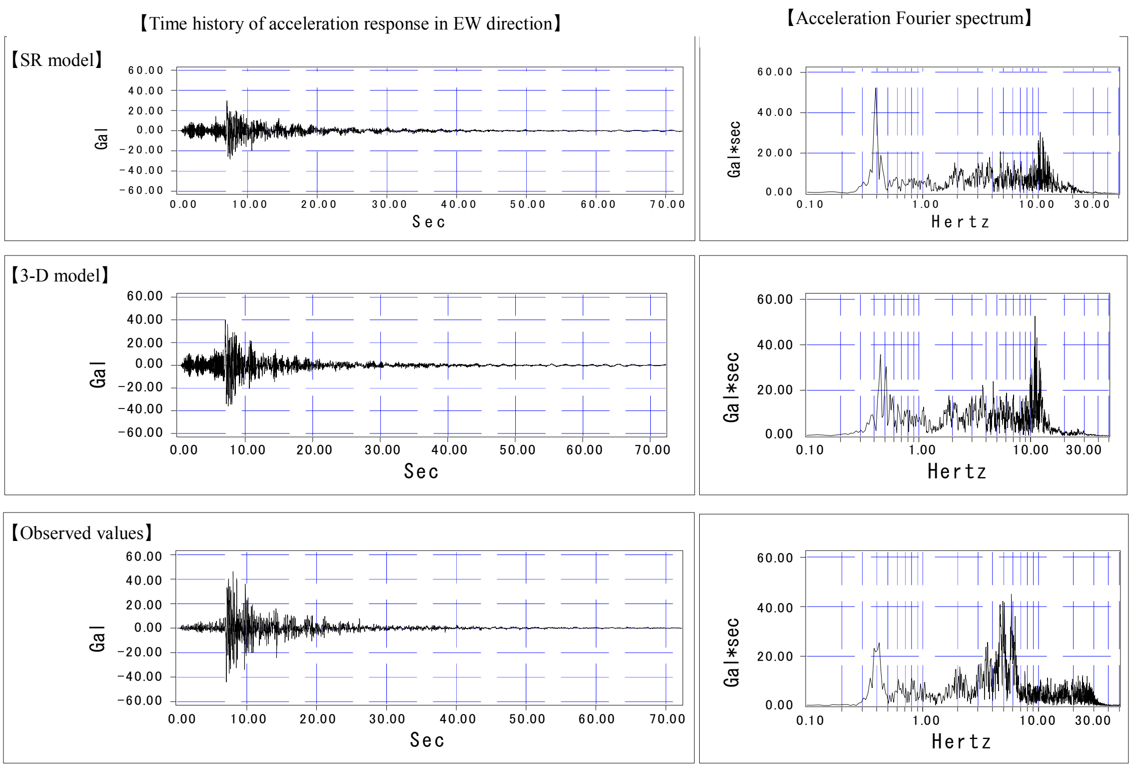


Fig. 4-19(a) Results of 3-D model analysis (Acceleration in EW direction) [23]

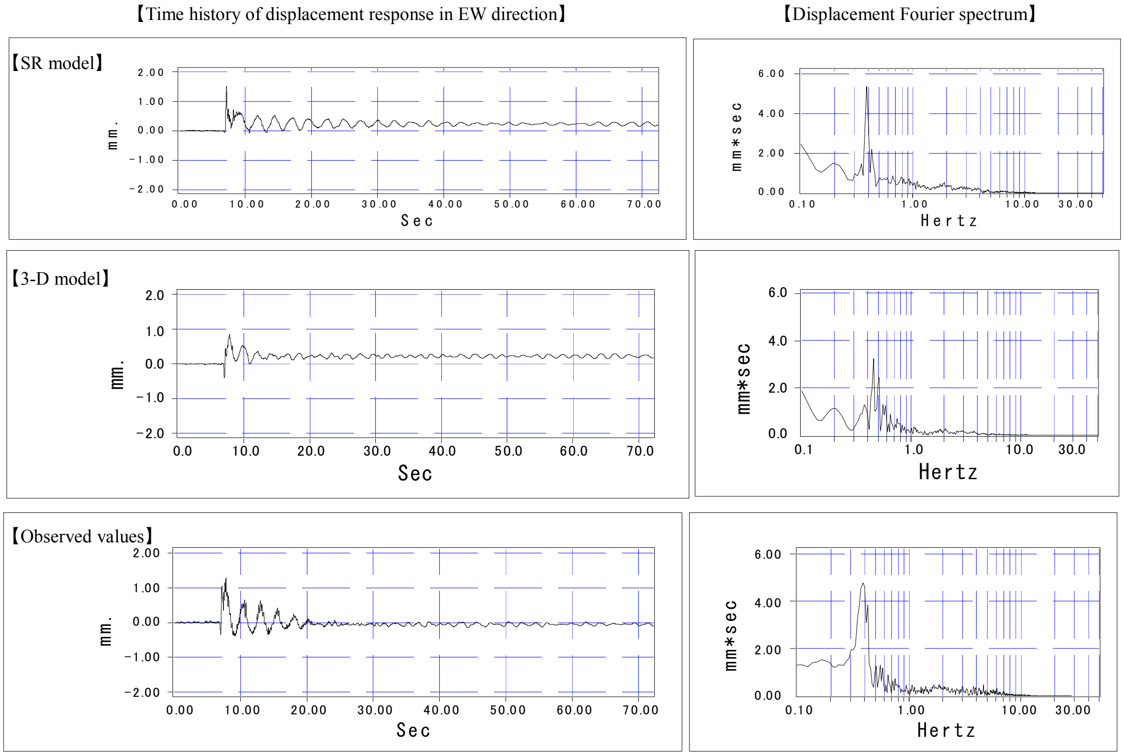


Fig. 4-19(b) Results of 3-D model analysis (Displacement in EW direction) [24]

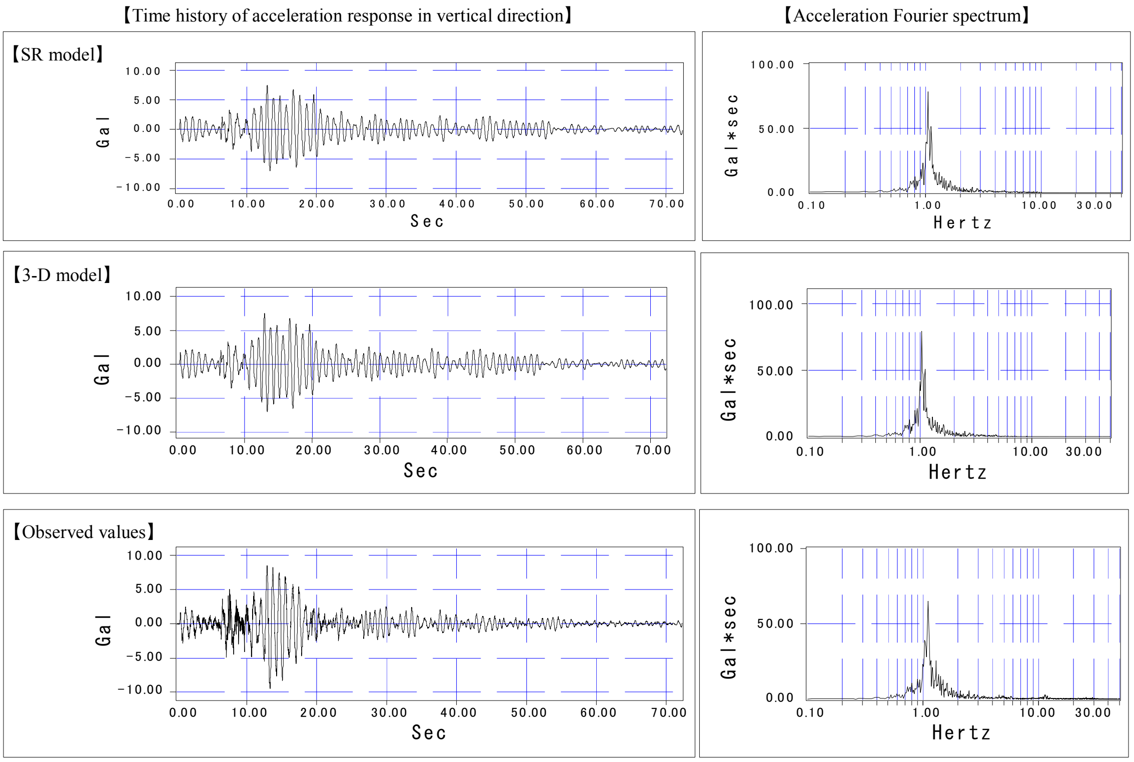


Fig. 4-19(c) Results of 3-D model analysis (Acceleration in vertical direction) [25]

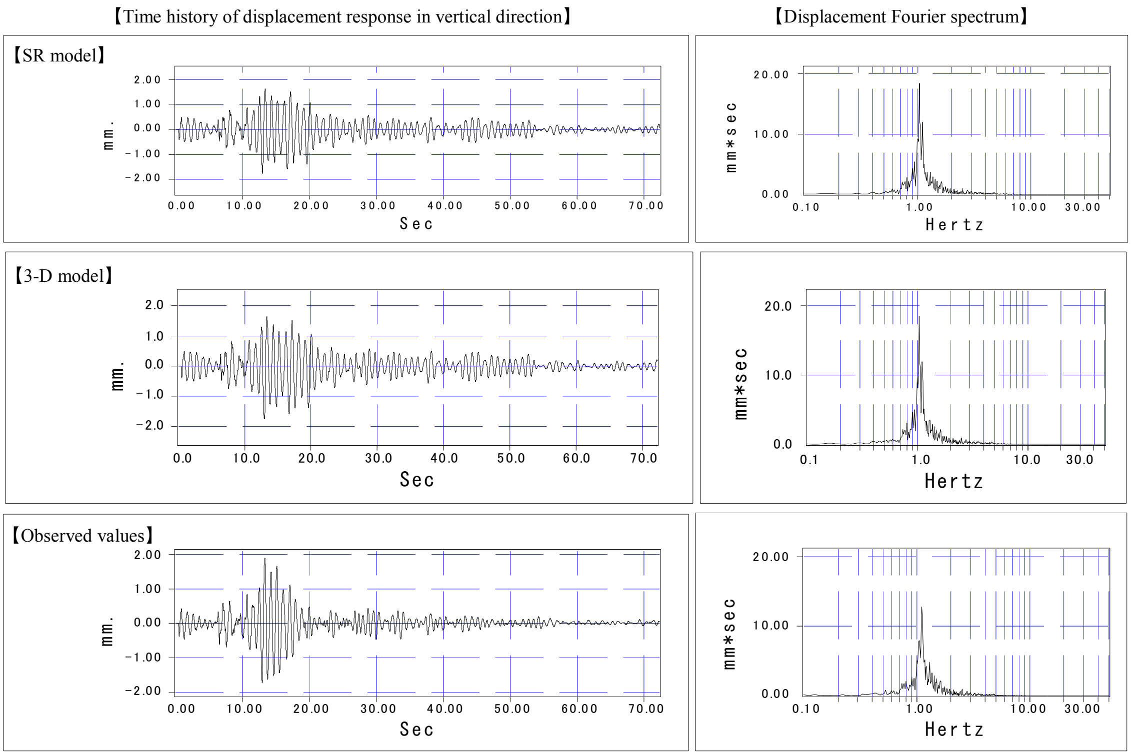


Fig. 4-19(d) Results of 3-D model analysis (Displacement in vertical direction) [26]

2.3 Multi-layer Rubber Bearing and Coil Spring type 3-D Equipment Isolation system

2.3.1 Design and configuration of seismic isolation system

(1) Design specification

Table 4-3 shows vibration characteristics of the 3-D equipment isolation system. The horizontal and vertical seismic isolation devices from which these vibration characteristics can be obtained were selected by assuming that horizontal natural frequency, the vertical oscillation frequency, the damping ratios in the horizontal and vertical directions are 0.5Hz, 2.0Hz, 0.2 and 0.3, respectively.

Especially, the vertical natural frequency needs to be determined by taking into consideration various conditions including the seismic isolation capabilities, supporting capabilities and rocking motion. In other words, if the natural frequency is reduced in order to increase the seismic isolation effect, the supporting capabilities for the vertical load will decrease, and rocking motion will increase. Considering the dominant frequency of the ground and the natural frequencies of the buildings and components, the setting range of the vertical natural oscillation frequency is appropriate to be between 1Hz and 4Hz (refer to Fig. 4-20). Concerning the ball bearing and air spring type 3-D base isolation system, whose seismic response has been observed under the condition of natural seismic motions, the vertical natural frequency is set at the lower limit of 1.0Hz. Therefore, in this system, the vertical natural frequency is set at 2.0Hz in order to compare and analyze the seismic isolation capabilities and dynamic response.

Table 4-3 Design vibration characteristics of the 3-D equipment isolation system

	Horizontal seismic isolation device	Vertical seismic isolation device
Sustained load	22tf	20tf
Natural frequency	0.5Hz	2.0Hz
Damping ratio	0.2	0.3

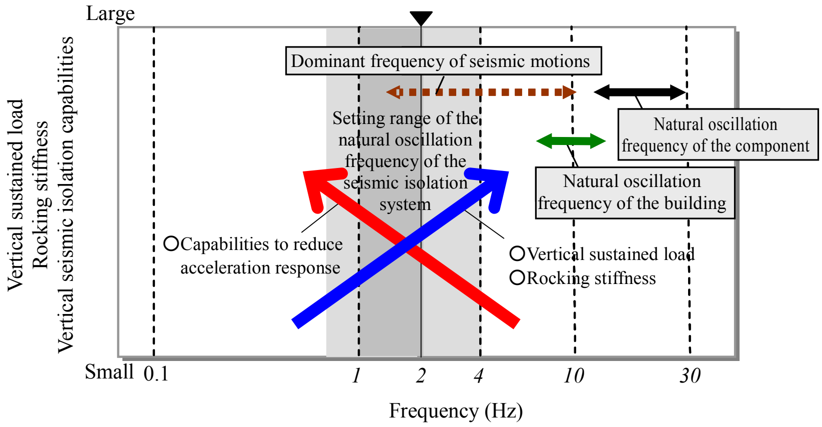


Fig. 4-20 Conditions to be considered when deciding the vertical seismic isolation natural frequency[27]

(2) Configuration of the 3-D equipment isolation system

1) Configuration of the base isolation system

Fig. 4-21 shows the overview of the 3-D equipment isolation system. As the figure shows, the base isolation system consists of the following devices:

① Horizontal seismic isolation devices (4 multi-layer laminated rubber bearings)

② Vertical seismic isolation devices (8 coil springs)

③ Damping devices (2 oil dampers in each of the NS and EW directions, and 8 dampers in vertical direction)

④ Horizontal and vertical seismic isolation base frame

⑤ Concrete blocks (assuming the component, hereafter abbreviated as C.B.)

In this base isolation system, multi-layer laminated rubber bearings are installed in four corners to support the horizontal seismic isolation base frame. Then, on the horizontal base frame, the coil springs accommodated in the case are arranged and fixed in a regular octagon shape to support the vertical seismic isolation base frame. The component is mounted on these base frames to be seismic isolated in both horizontal and vertical directions. In addition, (removable) oil dampers are installed between the floor and the horizontal seismic isolation base frame in the horizontal direction, and installed at the center of each coil spring case in the vertical direction.

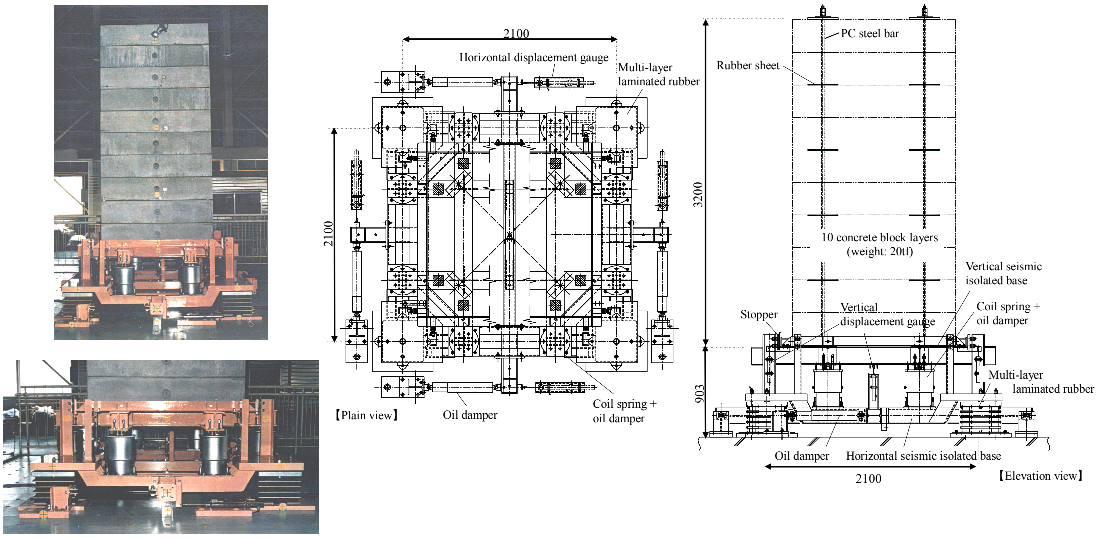


Fig. 4-21 Overview of the 3-D equipment isolation system[28]

2) Base isolated components and concrete blocks

A nuclear power plant is a composite structure consisting of approximately 2 million components. These components are roughly divided into non-safety components related to operation, and safety components serving to mitigate progress of an incident under an accident condition. In the seismic probabilistic safety assessment (PSA) targeting nuclear facilities, accident sequences, systems and components important to safety are identified, and equipment isolation is intended for these important components. Moreover, although the shapes and dimensions of the components vary significantly, their horizontal natural frequencies are in the range of 10Hz to 20Hz, and the vertical natural frequencies are estimated to be in the higher band.

Weight of a component is an especially important condition when choosing a seismic isolation device taking into consideration of the natural frequency and the supporting method of the equipment isolation system.

For the 100tf class components, rubber bearing which is the most popular horizontal seismic isolation device can be applied. However, for those middle- to small-sized components whose weight is at or less than 40t, it is difficult to apply rubber bearing to obtain the natural frequency required for the seismic isolation system (at or less than 0.5Hz). As a result, there are many challenges to be overcome in the design process which includes selection of a seismic isolation device.

Therefore, in this seismic isolation system, it was decided to mount a C.B. with the weight of 20tf assuming it to be a middle-sized class component. Furthermore, the ratio between the width and the height was set to be 1:2 so that rocking motion, which causes problem in the 3-D seismic isolation, would occur. Also, for the sake of easy weight adjustment, manufacture and assembly and disassembly, 10 concrete blocks, each of which was 1.6m by 1.6m by 32cm (weight: 2.0t/block) were stacked and secured to the vertical seismic isolated table by PC steel bars (height: 3.2m).

3) Horizontal seismic isolation device using multiple-layer laminated rubber bearing

Multi-layer laminated rubber bearing was used as a horizontal seismic isolation device. A unit of a multi-layer laminated rubber bearing consists of 4 small-sized rubber bearings (element laminated rubbers) fixed with a stabilizer plate, and these plates in needed number are stacked according to the design natural frequency. Multi-layer laminated rubber bearing is more stable to the vertical load in comparison to a single body rubber bearing, and smaller horizontal natural frequency can be obtained from the same sustained load. In addition, this allows more flexible design to the sustained load and the required horizontal natural frequency by choosing the size and the number of layers of the rubber bearings.

In this system, commercially available multi-layer laminated rubber bearing (MS055F20: manufactured by Bridgestone Corporation), from which approximately 0.5Hz of natural frequency could be obtained against the load of 5tf, was used. The number of layers of the laminated rubber was adjusted to be 5, and natural-rubber based low damping material was used for element laminated rubber. As the sustained load of the horizontal seismic isolation device was approximately 22.7t (5.7tf per 1 multi-layer laminated rubber), including C.B. and seismic isolation base frame, the natural frequency obtained by the multi-layer laminated rubber bearing would be 0.45Hz. The design allowable displacement (allowable deformation of each element laminated rubber × number of layers × recommended load/working load) is estimated to be approximately 9cm.

4) Coil spring vertical seismic isolation device

In this system, it was determined to support the load of approximately 20.6tf by 8 coil springs, and the following specifications were adopted for the design natural frequency of 2.0Hz:

○ Spring constant (per 1 coil spring) : 415kgf/cm

○ Tolerable displacement : ±5cm

Coil springs were installed in the steel casing pipe so that coils are displaced only in the vertical direction. Moreover, stopper bolts were fixed to the coil cases to prevent excessive deformation of the coils.

5) Oil damper in the horizontal direction

The damping ratio of the horizontal oil damper was adjusted to be approximately 0.2 to the natural frequency of 0.45Hz, and the following specifications were adopted. The oil dampers are supposed to have the damping capability almost proportional to velocity.

○ Damping coefficient (per oil damper) : 13.2kgfsec/cm

○ Allowable displacement : ±15cm

6) Oil damper in the vertical direction

The damping ratio of the vertical oil damper was determined to be approximately 0.3 to the natural frequency of 2.0Hz, and the specifications were set as follows. The oil dampers are supposed to have the damping capability almost proportional to velocity.

○ Damping coefficient (per oil damper) : 23.1kgfsec/cm

○ Allowable displacement : ±5cm

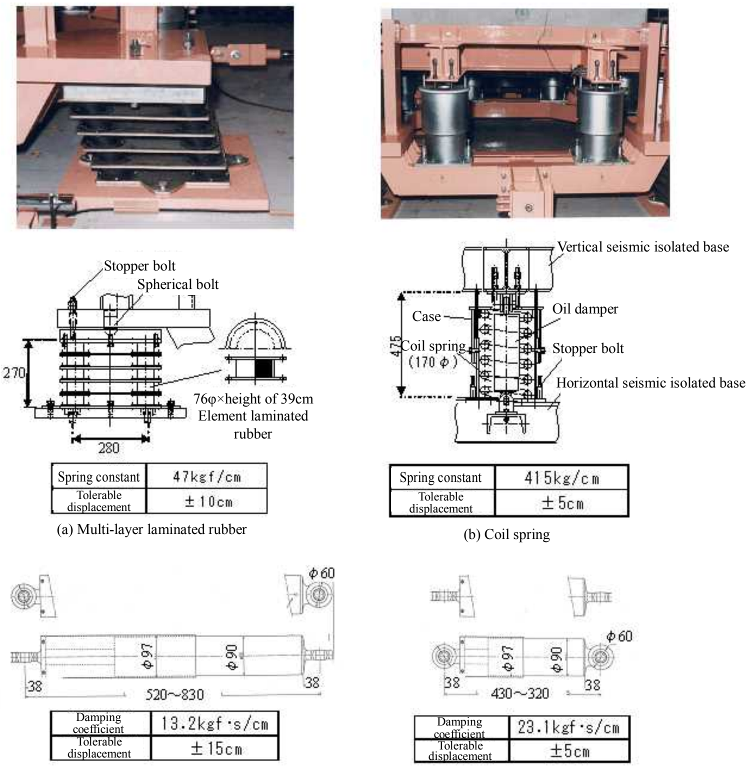


Fig. 4-22 Details of the 3-D seismic isolation device[29]

2.3.2 3-D vibration characteristics analysis

(1) Horizontal static force test

In the horizontal static force test, the horizontal seismic isolation base frame was pushed and pulled to X and Y directions by the screw jack (allowable load of 5tf) as is shown in Fig. 4-23 and to measure the load-horizontal displacement relation and the restoring force characteristics of multi-layer laminated rubber was obtained. Then, forced displacement of ±10mm, ±25mm, ±50mm, ±75mm, ±100mm at the maximum was applied repeatedly for 2 cycles. The load-displacement relation obtained by the force test shows the restoring force characteristics of 4 multi-layer rubber units.

Static force test was omitted in the vertical direction partly because the restoring characteristics of the coil springs were linear and less likely to vary, and also because considerably large equipment was required for the test and force application was difficult.

(2) Horizontal free vibration test

Free vibration was generated by pulling out the pins connecting the top of the jack and the seismic isolation base frame by a hydraulic jack, after providing initial displacement (25mm, 50mm, 100mm) in the horizontal direction by a jack for the static force application test, as Fig. 4-23 shows. During the free vibration, the acceleration at each section of the seismic isolation system and the horizontal displacement of the seismic isolated base were measured (refer to Fig. 4-24). Then, the horizontal natural frequency and the damping ratio were obtained based on the displacement time-history.

Concerning the vertical direction, the natural frequency and the damping ratio were identified by the sine sweep vibration test due to technical difficulty in generating free vibration.

(3) Horizontal and vertical sine wave sweep vibration tests

In the sine wave sweep vibration test, the vibration table specified in Table 4-4 was used. A sine wave of a constant acceleration amplitude (5Gal-40Gal) was input, while changing the frequency (horizontal direction: 0.3-30Hz, vertical direction: 0.8Hz-30Hz, interval: 0.02-0.1Hz), then the acceleration and the displacement of each section of the seismic isolation system were measured in a similar way to the free vibration test (Refer to Fig. 4-24). Then the horizontal and vertical natural frequencies, vibration modes and damping ratios were identified based on the resonant response characteristics of each section of the seismic isolation system obtained by applying vibration.

Table 4-4 List of specification of measurement devices[30]

Names of the measurement devices	Manufacturers and types	Specifications
Load cell	Kyowa Electronic Instruments: LUK-5TBS	Rating capacity:±5tf, rating output: 2mv/v (4000μs) ±1%
Horizontal displacement gauge	Kyowa Electronic Instruments: DLT-150AS	Rating capacity: ±150mm, rating output: 2mv/v (4000μs) Response frequency:DC-10Hz
Vertical displacement gauge	Kyowa Electronic Instruments: DLT-50AS	Rating capacity: ±50mm, rating output: 2mv/v (4000μs) Response frequency:DC-20Hz
Acceleration meter for horizontal direction	Kyowa Electronic Instruments: AS-2GB	Rating capacity: ±2G, rating output: 0.5mv/v (1000μs) Response frequency:DC-60Hz
Acceleration meter for vertical direction	Kyowa Electronic Instruments: AS-5GB	Rating capacity: ±5G, rating output: 0.5mv/v (1000μs) Response frequency:DC-100Hz
A/D converter	-	Sampling frequency: 256Hz, 20Hz digital low pass filter

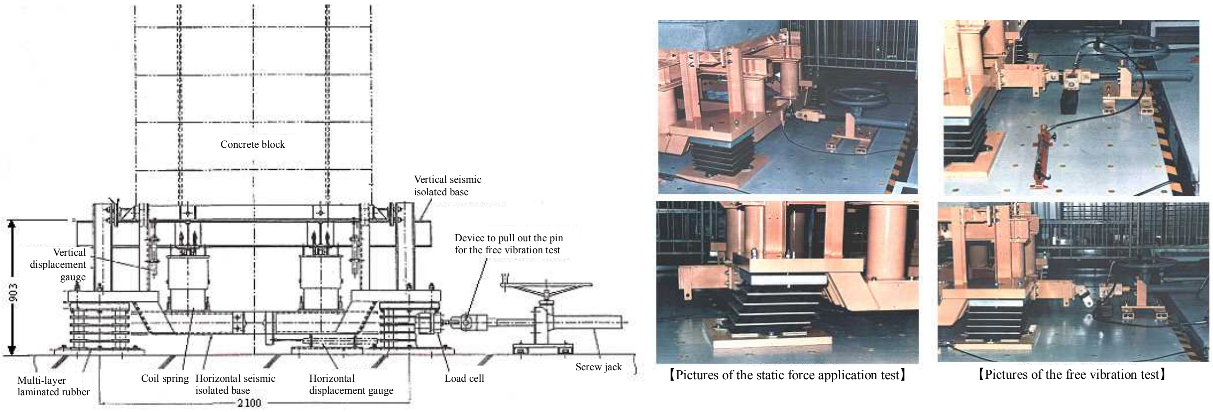


Fig. 4-23　Methods of static force test and free vibration test[31]

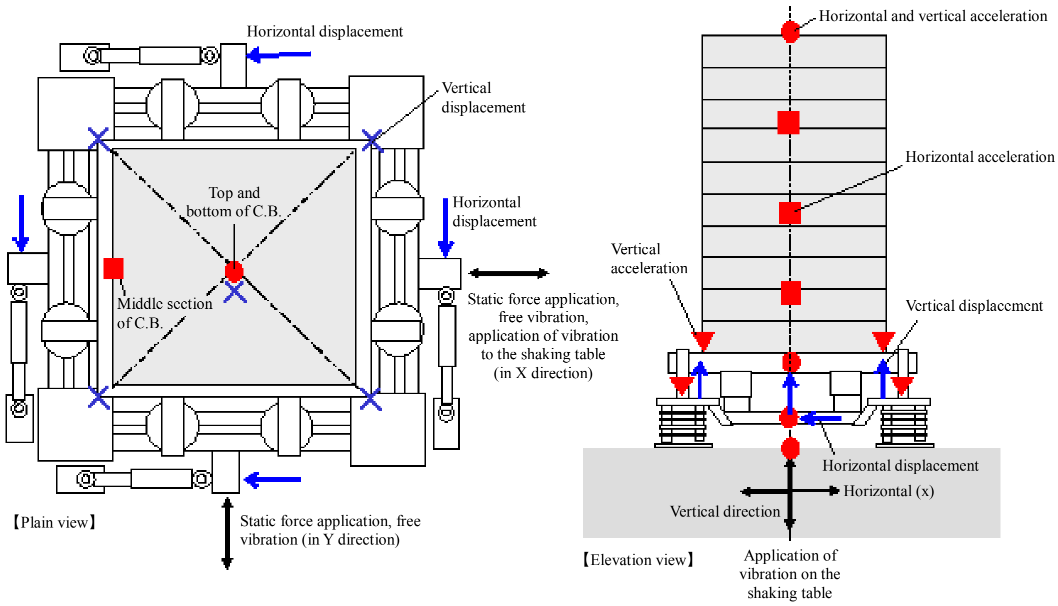


Fig. 4-24　Locations of displacement gauges and acceleration meters for characteristic tests[32]

2.3.3 Results of the vibration characteristics tests of the 3-D seismic isolation system

(1)　Horizontal static force test

Table 4-5 shows the horizontal rigidness obtained from the static force test of the 3-D seismic isolation system, and Fig. 4-25 shows the restoring force characteristics of the 3-D seismic isolation system. On the same figure, the restoring force characteristics are superimposed, when the maximum displacement of ±25mm, ±50mm and ±100mm was applied. Based on these results, the following information was obtained concerning the restoring force characteristics.

① Equivalent stiffness at the maximum displacement in each test agrees very well and the restoring force characteristics in X and Y directions are almost the same. However, the system with dampers formed a larger hysteresis loop than the system without dampers. This is considered to be due to the influence of friction resistance of the oil damper seal.

② Equivalent stiffness at the maximum displacement in each force application cycle gradually decreases as the amount of displacement increases, showing a sort of “softening type” hysteresis loop characteristics. However, the change in stiffness in the displacement range of 10mm to 50mm, which is considered to be the major vibration region in time of an earthquake, was approximately 10%, and thus the impact on the changes in the natural frequency is considered to be small and almost linear.

③ Restoring force characteristics at the displacement are covered by large displacement loop, being reproductive and showing constant aspects.

(2) Free vibration test and sine wave sweep excitation test

1) 3-D seismic isolation system without dampers

Fig. 4-26 shows the damping coefficients and the natural frequencies calculated per cycle, assuming the local maximum point in each cycle in displacement time history obtained from the horizontal free vibration test with the initial displacement of approximately 100mm as the initial amplitude. Fig. 4-27 shows the acceleration resonance curve near the horizontal primary mode (horizontal excitation frequency: 0.3H - 0.5Hz, interval: 0.02Hz, acceleration amplitude: 4 Gals), the same curve near the horizontal secondary mode (horizontal excitation frequency: 1.2Hz - 1.6Hz, interval: 0.1Hz, acceleration amplitude: 25 Gals), and the same curve near the vertical primary mode (the range of vertical oscillation frequency: 0.8 - 3.0 Hz, interval: 0.1Hz, acceleration amplitude: 5 Gals), as the results of the sine wave sweep excitation tests. Fig. 4-28 shows the vibration mode shapes obtained from the acceleration distribution of each section of the seismic isolation system. The time history of the horizontal displacement was filtered by the 1.1 Hz low pass filter in order to remove the influence of the secondary vibration mode (approximately 1.5Hz) and to abstract the vibration wave form of the primary vibration mode.

①The natural frequencies of the horizontal primary mode, the horizontal secondary mode and the vertical primary mode are respectively identified as 0.4Hz, 1.45Hz and 2Hz from each acceleration resonance curve. Also, the primary natural frequency obtained from the time history of displacement during the free vibration test is from 0.39 to 0.4Hz. Although it is on a slightly declining trend at the large displacement, it indicates almost the constant value. This trend is considered to be due to the influence of softening of stiffness. According to the results of the sine wave excitation test carried out at the interval of 0.1Hz in the frequency range of 1Hz – 30Hz in horizontal direction, and in the range of 2.2Hz – 30Hz in vertical direction, resonance frequency is not observed. Therefore, the above-mentioned three modes are thought to be the major vibration mode of the 3-D seismic isolation system.

②Based on the acceleration distribution at each point, the horizontal primary mode is a vibration mode in which rocking motion that rotates around the vertical seismic isolated base is combined to the translation mode of the horizontal seismic isolation base frame. The horizontal secondary mode has opposite phases at the top and the bottom of C.B., it shows almost the same level of amplification ratio, and indicates minute value at the center of C.B. Therefore, the horizontal secondary mode is a rigid body rocking mode that rotates around the neighborhood of the center of C.B. Furthermore, as the vertical primary mode has the same phases at the top and the bottom of C.B., and shows almost the same level of acceleration response amplification ratio, it is a translation mode of C.B. as a rigid body.

③The damping ratio for the horizontal primary mode is in the range of 0.045 to 0.047, based on the time history of displacement in the free vibration test. The damping ratio is at a constant level in the large amplitude region, and on an increasing trend in the small amplitude region. It is assumed to be due to the influence of friction inside the material caused by natural rubber and additives that are the material of laminated rubber, based on the loop characteristics obtained from the static force test. Generally, this type of loop attenuation has characteristics inversely proportional to displacement. Also, the damping ratio to the vertical primary mode is estimated to be approximately 0.02 based on the acceleration response amplification ratio.

④According to the free vibration test results, the natural frequencies and the damping ratios indicate similar values in X and Y directions, and anisotropic nature is not observed regarding the vibration characteristics in horizontal direction.

2) 3-D seismic isolation system with dampers

In the sine wave sweep excitation test, the acceleration amplitudes near the horizontal primary mode, near the horizontal secondary mode and near the vertical primary mode were to be 15 Gals, 50 Gals and 40 Gals, respectively.

① Similar to the case without dampers, the natural frequencies of the horizontal primary mode, horizontal secondary mode and vertical primary mode are 0.4Hz, 1.45Hz and 2Hz, respectively, based on the acceleration resonance curve, and these are considered as the major vibration modes. However, due to the oil damper effect, the acceleration response amplification ratio of each resonance frequency considerably decreases in comparison to the case without dampers. Especially, the response amplification ratio of the horizontal secondary mode is extremely small (approximately 0.5), and no clear peak is observed.

② The damping ratio for the horizontal primary mode is 0.23 in the large amplitude region with, based on the time history of displacement in the free vibration test. Due to the damper effect, attenuation of vibration is extremely fast in comparison to the case without dampers.

③ The damping ratio to the vertical primary mode is estimated to be approximately 0.3 based on the acceleration response amplification ratio.

④ According to the free vibration test results, the natural frequencies and the damping ratios indicate similar values in X and Y directions, and anisotropic nature is not observed regarding the vibration characteristics in horizontal direction.

3) Horizontal seismic isolation system without dampers

In the sine wave sweep excitation test, the horizontal excitation frequencies near the horizontal primary mode were to be 0.4 Hz - 0.6 Hz, with the interval of 0.02 Hz and acceleration amplitude of 6 Gals, while the horizontal excitation frequencies near the horizontal secondary mode were to be 3.5 Hz - 6.5 Hz, with the interval of 0.1 Hz and acceleration amplitude of 40 Gals, and in the vertical direction, the vertical excitation frequencies were to be 1 Hz - 30 Hz, with the interval of 0.1Hz and acceleration amplitude of 10 Gals.

① The natural frequencies of the horizontal primary mode, horizontal secondary mode and vertical primary mode are 0.45 Hz, 5.2 Hz and 9.9 Hz, respectively, based on the acceleration resonance curve, and these are considered as the major vibration modes. However, the response amplification ratio of the horizontal secondary mode is extremely small, being approximately 0.25. Also, the primary natural frequency obtained from the displacement time history observed in the free vibration test is 0.46 - 0.48 Hz in the amplitude region at not less than 10mm. Thus, the primary natural frequency tends to slightly decrease as the vibration amplitude increases due to the softening trend of stiffness.

② Based on the distribution of acceleration at each point, the horizontal primary mode is the translation mode of the horizontal seismic isolated base frame, and the horizontal secondary mode is the rocking mode of an entire C.B. with the bottom of C.B. serving as a fixed point. Moreover, the vertical primary mode is the vertical vibration mode of an entire C.B. supported on the multi-layer laminated rubber bearing and the vertical springs located on the horizontal seismic isolated base frame. In this case, as the damping is extremely small due to the structural reasons, the acceleration response amplification ratio of the vertical primary mode becomes extremely large, and influences response in horizontal direction, and provides apparent resonance peak in the resonance response frequency region of this mode. Also, if the excitation is applied only in horizontal direction, vertical vibration sensitively responds due to the vibration noise of the shaking table.

③ From the displacement time history of the free vibration test, the damping ratio for the horizontal primary mode is 0.045 - 0.047, which is almost constant to the vibration amplitude. The damping ratio for the vertical primary mode is estimated to be approximately 0.02 based on the acceleration response amplification ratio.

④The damping ratios and the natural frequencies indicate similar values in X and Y directions, and anisotropic nature is not observed regarding the vibration characteristics in horizontal direction.

4) Horizontal seismic isolated system with dampers

In the sine wave sweep excitation test, the horizontal excitation frequencies near the horizontal primary mode were to be 0.35 Hz - 0.7 Hz, with the interval of 0.05 Hz and acceleration amplitude of 20 Gals, while the horizontal excitation frequencies near the horizontal secondary mode were to be 3.5 Hz - 6.5 Hz, with the interval of 0.1 Hz and acceleration amplitude of 40 Gals, and in the vertical direction, the vertical excitation frequencies were to be 1 Hz - 30 Hz, with the interval of 0.1Hz and acceleration amplitude of 10 Gals.

①The natural frequencies of the horizontal primary mode, horizontal secondary mode and vertical primary mode are 0.46 Hz, 5.2 Hz and 9.9 Hz, respectively, based on the acceleration resonance curve, and these are considered as the major vibration modes. The response amplification ratio of the horizontal primary mode considerably decreases due to the effects of the damper. Similar to the case without dampers, the primary natural frequency obtained from the displacement time history observed in the free vibration test is 0.46 to 0.48 Hz in the amplitude region at not less than 10mm.

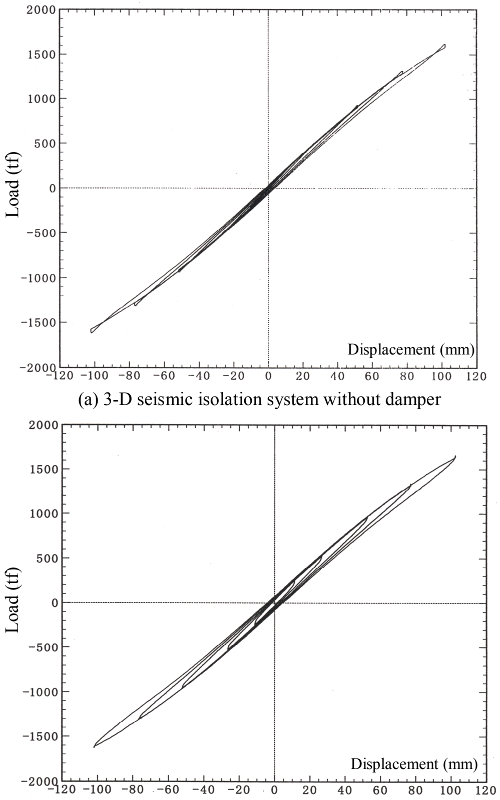
②The damping ratios are between 0.25 and 0.26 in the relatively large amplitude region with the amplitude at not less than 20mm, based on the time history of displacement in the free vibration test. However, in the region with the amplitude at below 10mm, the damping ratio increases to at equal or more than 0.30, probably due to the friction of the axial seal of the oil damper.

③ The damping ratios and the natural frequencies indicate similar values in X and Y directions, and anisotropic nature is not observed regarding the vibration characteristics in horizontal direction.

Table 4-6 shows the outline of vibration characteristics of each seismic isolation system obtained from the characteristic tests

Table 4-5 Horizontal stiffness of the 3-D seismic isolation system and horizontal seismic isolation system[33]

Type of seismic isolation system	Direction of force application	Maximum displacement amplitude (mm)				
		10	25	50	75	100
3-D seismic isolation without dampers	X	19.7	18.9	17.8	16.9	15.7
3-D seismic isolation with dampers	X	20.2	19.1	18	17	15.9
Horizontal seismic isolation without dampers	X	20	19.1	18	16.8	15.7
	Y	20.2	19.3	18.1	17	15.7
Horizontal seismic isolation with dampers	X	19.7	19	18	16.9	15.7



(a) 3-D seismic isolation system without damper

(b) 3-D seismic isolation system with damper

Fig. 4-25 Restoring force characteristics of 3-D seismic isolation system[34]

Table 4-6 List of vibration characteristics of component base seismic isolation system[35]

	Natural oscillation frequency (Hz)	Acceleration response amplification ratio		Vibration modes	Damping ratios	
		Without dampers	With dampers		Without dampers	With dampers
3-D seismic isolation	0.40	18.1*	4.40	Horizontal primary (translation + rocking)	Horizontal: 0.045	Horizontal: 0.23
	1.45	4.9	0.50	Horizontal secondary (C.B. rigid body rocking)	Vertical: 0.02	Vertical: 0.3
	2.00	25.9	1.64	Vertical primary (translation)		
Horizontal seismic isolation	12.0	12.0	2.8	Horizontal primary (translation)	Horizontal: 0.045	Horizontal : 0.25
	0.27	0.27	0.85	Horizontal secondary (C.B. rigid body rocking)	Vertical:0.02	Vertical: 0.02
	31.8	31.8	30.1	Vertical primary (translation)		
	0.30	0.30	0.35	Horizontal tertiary		

*1 ---Results of the sine wave sweep test

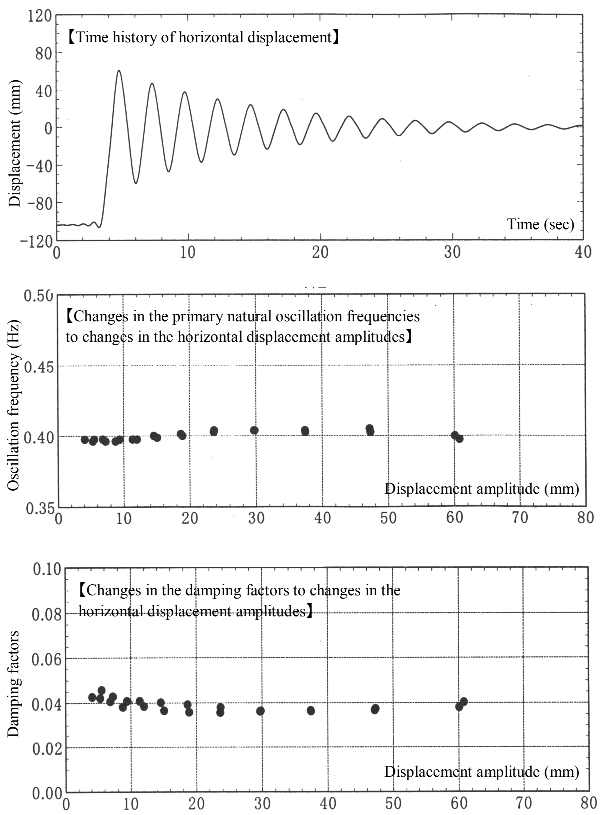


Fig. 4-26 Results of the free vibration test for 3-D seismic isolation system without dampers[36]

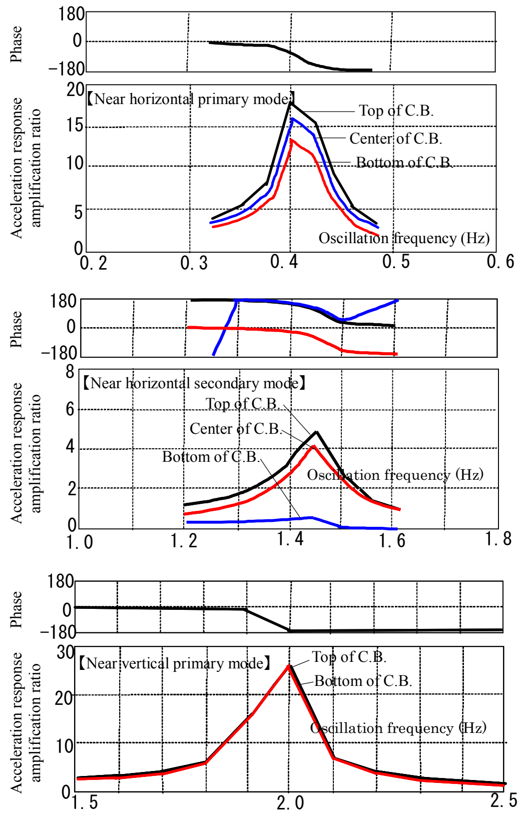


Fig. 4-27 Acceleration resonance curve of the 3-D seismic isolation system without dampers[37]

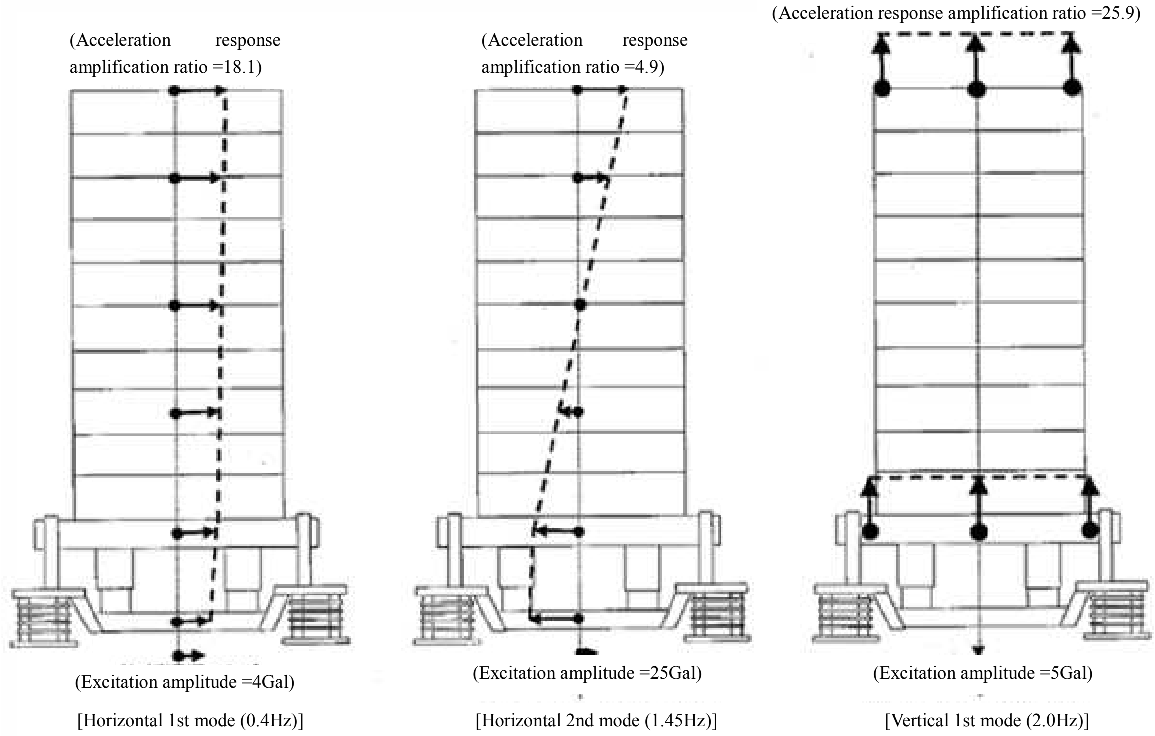


Fig. 4-28 Vibration mode of the 3-D seismic isolation system without damper[38]

2.3.4 Sine Wave Parametric Excitation Test

(1) Outline of excitation test

1) Excitation case

In the sine wave excitation test, the resonance characteristics were examined by applying 30 sine waves of specific frequencies simultaneously in horizontal and vertical directions (primary and secondary natural frequencies) at which the response of the seismic isolation system is predominant. As is shown in Table 4-7, the frequency ratio, amplitude ratio and phase difference of the input wave in horizontal and vertical directions were combined as parameters and applied in order to evaluate the influence of each combination of parameters on the 3-D coupled vibration of the seismic isolation system. Excitation test was performed in both cases of with and without the damper so as to compare and study the difference of response characteristics of both cases. The following are the major combinations of excitation parameters.

① Influence of vertical oscillation amplitude on the horizontal primary mode

- Frequency : $f_H = f_V$ (f_H = 0.4Hz:Primary natural frequency)
- Amplitude : A_H = Approx. 4 Gals $A_V = \alpha A_H$ (α = 1, 2, 3, 5)

② Influence of vertical oscillation frequency on the horizontal primary mode

- Frequency : $f_V = \alpha f_H$ (α = 1, 2, 3, 4, 5)
- Amplitude : A_H = Approx. 4 Gals $A_V = \beta A_H$ β = 1, 2,3, 4, 5)

③ Influence of vertical oscillation phase difference on the horizontal primary mode

- Frequency : $f_H = f_V$

・Phase difference : $\varphi_V - \varphi_H = 0°$, -90°, 45°, 90°, 180°

・Amplitude : A_H = Approx. 4 Gals $A_V = \alpha A_H$ (α : 3-4cases)

④ Influence of vertical oscillation on the horizontal secondary mode

・Frequency : $f_H = f_H$ (f_{H2}=1.45Hz: Secondary natural oscillation frequency)

$f_V = \alpha f_{H2}$ (α : Approx. 2 cases)

・Amplitude : A_H = Approx. 10Gals $A_V = \beta A_H$ (β : Approx. 2cases)

The above parameter values are the control target values of the shaking table and thus, in the actual excitation test, input values are slightly different.

2) Excitation method

Input sine wave in horizontal direction, u_H, input sine wave in vertical direction, u_V, are defined as follows:

$$u_H = A_H \sin((f_H/2\pi)t - (\varphi_H/180)\pi) \quad (0 \leqq t \leqq 30/f_{H1})$$
$$= 0 \quad (30/f_{H1} < t)$$
$$u_V = A_V \sin((f_V/2\pi)t - (\varphi_V/180)\pi) \quad (0 \leqq t \leqq 30/f_{H1})$$
$$= 0 \quad (30/f_{H1} < t)$$

Amplitude increasing from the amplitude 0 to the design amplitude, and decreasing from the design amplitude to the amplitude 0, was applied to 5 waves from the start and completion of horizontal sine wave excitation for smooth start and completion of excitation. Concerning sine wave in vertical direction, amplitude changing of the same interval of time as amplitude changing in horizontal direction was applied.

The measurement of acceleration and displacement at each section of the test specimen was performed in the same way as the sine wave sweep excitation test.

(2) Sine wave excitation test

The following is the outline of the knowledge and findings about the influence of the 3-D coupled vibration obtained from simultaneous excitation in both horizontal and vertical directions using sine waves, in which the frequency ratio, amplitude ratio and phase difference were combined as parameters.

1) In the case without dampers, although there seems to be a tendency that the horizontal response acceleration slightly increases in the resonance region of the horizontal secondary mode and the vertical primary mode due to the influence of the rapid increase of rocking motion and the response acceleration in vertical direction during the excitation in the dominant frequency region of the 3-D seismic isolation system, no unstable vibration phenomenon such as parametric resonance occurred.

2) In the case with dampers, response amplification by high-order mode of the seismic isolation system is sufficiently restricted and no influence of the coupled vibration is observed.

Table 4-7(a) List of sine wave parametric excitation cases (without dampers) [39]

Test cases	Horizontal input		Vertical input		Amplitude ratio	Frequency ratio	Phase difference	Notes
	Oscillation frequency (Hz)	Acceleration (Gal)	Oscillation frequency (Hz)	Acceleration (Gal)	(α=Av/Ah)	(β=fv/fh)	(φ)	
M1-α0β0φ0	0.4	4.0 (3.53)	0.000	0.0 (0.00)	0.0	0.0	0.0	Standard for comparison
M1-α1β1φ0	0.4	4.0 (3.52)	0.400	4.0 (3.51)	1.0	1.0	0.0	Influence of the amplitude ratio and frequency ratio in the horizontal primary mode
M1-α1β2φ0	0.4	4.0 (3.57)	0.800	4.0 (3.10)	1.0	2.0	0.0	
M1−α1β3φ0	0.4	4.0 (3.59)	1.200	4.0 (2.99)	1.0	3.0	0.0	
M1-α1β4φ0	0.4	4.0 (3.76)	1.600	4.0 (3.36)	1.0	4.0	0.0	
M1-α1β5φ0	0.4	4.0 (3.53)	2.000	4.0 (3.26)	1.0	5.0	0.0	
M1-α2β1φ0	0.4	4.0 (3.90)	0.400	8.0 (8.79)	2.0	1.0	0.0	
M1-α2β2φ0	0.4	4.0 (3.65)	0.800	8.0 (8.23)	2.0	2.0	0.0	
M1-α2β3φ0	0.4	4.0 (3.52)	1.200	8.0 (8.16)	2.0	3.0	0.0	
M1-α2β4φ0	0.4	4.0 (3.69)	1.600	8.0 (8.02)	2.0	4.0	0.0	
M1-α2β5φ0	0.4	4.0 (3.72)	2.000	8.0 (6.50)	2.0	5.0	0.0	
M1-α3β1φ0	0.4	4.0 (4.01)	0.400	12.0 (13.13)	3.0	1.0	0.0	
M1-α3β2φ0	0.4	4.0 (3.55)	0.800	12.0 (12.45)	3.0	2.0	0.0	
M1-α3β3φ0	0.4	4.0 (3.59)	1.200	12.0 (12.26)	3.0	3.0	0.0	
M1-α3β4φ0	0.4	4.0 (3.67)	1.600	12.0 (12.24)	3.0	4.0	0.0	
M1-α5β1φ0	0.4	4.0 (4.11)	0.400	20.0 (20.30)	5.0	1.0	0.0	
M1-α5β2φ0	0.4	4.0 (3.58)	0.800	20.0 (19.25)	5.0	2.0	0.0	
M1-α5β3φ0	0.4	4.0 (3.55)	1.200	20.0 (19.27)	5.0	3.0	0.0	
M1-α5β4φ0	0.4	4.0 (3.71)	1.600	20.0 (18.97)	5.0	4.0	0.0	
M1-α1β1φ-90	0.4	4.0 (3.47)	0.400	4.0 (3.85)	1.0	1.0	−90.0	Influence of the phase difference in the horizontal primary mode
M1-α1β1φ45	0.4	4.0 (3.78)	0.400	4.0 (4.14)	1.0	1.0	45.0	
M1-α1β1φ90	0.4	4.0 (3.68)	0.400	4.0 (3.76)	1.0	1.0	90.0	
M1-α1β1φ180	0.4	4.0 (3.43)	0.400	4.0 (4.30)	1.0	1.0	180.0	
M1-α2β1φ-90	0.4	4.0 (3.56)	0.400	8.0 (8.65)	2.0	1.0	−90.0	
M1-α2β1φ45	0.4	4.0 (3.81)	0.400	8.0 (8.80)	2.0	1.0	45.0	
M1-α2β1φ90	0.4	4.0 (3.79)	0.400	8.0 (8.82)	2.0	1.0	90.0	
M1-α2β1φ180	0.4	4.0 (3.01)	0.400	8.0 (9.10)	2.0	1.0	180.0	
M1-α3β1φ-90	0.4	4.0 (3.67)	0.400	12.0 (13.00)	3.0	1.0	−90.0	
M1-α3β1φ45	0.4	4.0 (4.00)	0.400	12.0 (13.28)	3.0	1.0	45.0	
M1-α3β1φ90	0.4	4.0 (3.62)	0.400	12.0 (13.39)	3.0	1.0	90.0	
M1-α5β1φ-90	0.4	4.0 (3.70)	0.400	20.0 (20.02)	5.0	1.0	−90.0	
M1-α5β1φ45	0.4	4.0 (4.11)	0.400	20.0 (20.40)	5.0	1.0	45.0	
M1-α5β1φ90	0.4	4.0 (3.68)	0.400	20.0 (20.32)	5.0	1.0	90.0	
M2-α0β0	1.45	10.0 (10.14)	0.000	0.0 (0.00)	0.0	0.0	0.0	Standard for comparison
M2-α1β0.5	1.45	10.0 (10.32)	0.725	10.0 (10.50)	1.0	0.5	0.0	Influence of the amplitude ratio and frequency ratio in the horizontal secondary mode
M2−α1β1	1.45	10.0 (10.49)	1.450	10.0 (10.22)	1.0	1.0	0.0	
M2-α1β2	1.45	10.0 (10.14)	2.900	10.0 (10.55)	1.0	2.0	0.0	
M2-α2β0.5	1.45	10.0 (10.12)	0.725	20.0 (19.41)	2.0	0.5	0.0	
M2-α2β1	1.45	10.0 (10.67)	1.450	20.0 (19.17)	2.0	1.0	0.0	
M2-α2β2	1.45	10.0 (10.08)	2.900	20.0 (19.40)	2.0	2.0	0.0	

Horizontal and vertical input……Values in ( ) are the input acceleration measured on the shaking table

Table 4-7(b) List of sine wave parametric excitation cases (with dampers) [40]

Test cases	Horizontal input		Vertical input		Amplitude ratio	Frequency ratio	Phase difference	Notes
	Oscillation frequency (Hz)	Acceleration (Gal)	Oscillation frequency (Hz)	Acceleration (Gal)	(α=Av/Ah)	(β=fv/fh)	(φ)	
M1-α0β0φ0	0.4	6.0 (5.28)	0.000	0.0 (0.00)	0.0	0.0	0.0	Standard for comparison
M1-α1β1φ0	0.4	6.0 (5.62)	0.400	6.0 (7.35)	1.0	1.0	0.0	Influence of the amplitude ratio and frequency ratio in the horizontal primary mode
M1-α1β2φ0	0.4	6.0 (5.37)	0.800	6.0 (4.76)	1.0	2.0	0.0	
M1−α1β3φ0	0.4	6.0 (5.27)	1.200	6.0 (4.90)	1.0	3.0	0.0	
M1-α1β4φ0	0.4	6.0 (5.17)	1.600	6.0 (4.66)	1.0	4.0	0.0	
M1-α1β5φ0	0.4	6.0 (5.33)	2.000	6.0 (6.69)	1.0	5.0	0.0	
M1-α2β1φ0	0.4	6.0 (5.61)	0.400	12.0 (12.67)	2.0	1.0	0.0	
M1-α2β2φ0	0.4	6.0 (5.24)	0.800	12.0 (11.55)	2.0	2.0	0.0	
M1-α2β3φ0	0.4	6.0 (5.35)	1.200	12.0 (11.63)	2.0	3.0	0.0	
M1-α2β4φ0	0.4	6.0 (5.28)	1.600	12.0 (11.43)	2.0	4.0	0.0	
M1-α2β5φ0	0.4	6.0 (5.92)	0.400	18.0 (18.08)	3.0	1.0	0.0	
M1-α3β1φ0	0.4	6.0 (5.25)	0.800	18.0 (16.68)	3.0	2.0	0.0	
M1-α3β2φ0	0.4	6.0 (5.28)	1.200	18.0 (16.76)	3.0	3.0	0.0	
M1-α3β3φ0	0.4	6.0 (5.31)	1.600	18.0 (16.31)	3.0	4.0	0.0	
M1-α3β4φ0	0.4	6.0 (5.28)	0.000	0.0 (0.00)	0.0	0.0	0.0	
M1-α1β1φ-90	0.4	6.0 (5.03)	0.400	6.0 (5.35)	1.0	1.0	−90.0	Influence of the phase difference in the horizontal primary mode
M1-α1β1φ45	0.4	6.0 (5.59)	0.400	6.0 (5.66)	1.0	1.0	45.0	
M1-α1β1φ90	0.4	6.0 (5.44)	0.400	6.0 (5.55)	1.0	1.0	90.0	
M1-α1β1φ180	0.4	6.0 (4.80)	0.400	6.0 (5.82)	1.0	1.0	180.0	
M1-α2β1φ-90	0.4	6.0 (4.95)	0.400	12.0 (10.98)	2.0	1.0	−90.0	
M1-α2β1φ45	0.4	6.0 (5.76)	0.400	12.0 (11.60)	2.0	1.0	45.0	
M1-α2β1φ90	0.4	6.0 (5.38)	0.400	12.0 (11.42)	2.0	1.0	90.0	
M1-α2β1φ180	0.4	6.0 (4.67)	0.400	12.0 (11.33)	2.0	1.0	180.0	
M1-α3β1φ-90	0.4	6.0 (4.85)	0.400	18.0 (17.51)	3.0	1.0	−90.0	
M1-α3β1φ45	0.4	6.0 (5.81)	0.400	18.0 (17.97)	3.0	1.0	45.0	
M1-α3β1φ90	0.4	6.0 (5.49)	0.400	18.0 (17.89)	3.0	1.0	90.0	
M1-α3β1φ180	0.4	6.0 (4.51)	0.400	18.0 (17.87)	3.0	1.0	180.0	
M2-α0β0	1.45	10.0 (10.18)	0.000	0.0 (0.00)	0.0	0.0	0.0	Standard for comparison
M2-α1β0.5	1.45	10.0 (9.97)	0.725	10.0 (10.45)	1.0	0.5	0.0	Influence of the amplitude ratio and frequency ratio in the horizontal secondary mode
M2−α1β1	1.45	10.0 (10.49)	1.450	10.0 (10.28)	1.0	1.0	0.0	
M2-α1β2	1.45	10.0 (10.29)	2.900	10.0 (10.45)	1.0	2.0	0.0	
M2-α2β0.5	1.45	10.0 (10.15)	0.725	20.0 (19.61)	2.0	0.5	0.0	
M2-α2β1	1.45	10.0 (10.83)	1.450	20.0 (19.30)	2.0	1.0	0.0	
M2-α2β2	1.45	10.0 (10.17)	2.900	20.0 (19.39)	2.0	2.0	0.0	

Horizontal and vertical input Values in ( ) are the input acceleration measured on the shaking table

Table 4-8 List of sine wave parametric excitation cases (without dampers) [41]

	Horizontal direction				Vertical direction			
	Input acceleration (Gal)	Acceleration at the top of C.B. (Gal)	Response amplification ratio	Horizontal displacement of seismic isolated base* (mm)	Input acceleration (Gal)	Acceleration at the bottom of C.B. (Gal)	Response amplification ratio	Displacement at the bottom of C.B. (mm)
M1-α0β0φ0	3.53	64.25	18.20	57.48	0.00	8.43	—	0.92
M1-α1β1φ0	3.52	61.23	17.39	54.76	3.51	14.00	3.99	0.87
M1-α1β2φ0	3.57	63.74	17.85	56.63	3.10	12.14	3.92	1.10
M1-α1β3φ0	3.59	63.76	17.76	57.38	2.99	12.71	4.25	1.20
M1-α1β4φ0	3.76	74.19	19.73	63.88	3.36	20.53	6.11	1.50
M1-α1β5φ0	3.53	83.01	23.52	62.25	3.26	68.88	21.13	4.48
M1-α2β1φ0	3.90	67.14	17.22	58.90	8.79	18.72	2.13	1.15
M1-α2β2φ0	3.65	65.49	17.94	58.75	8.23	20.12	2.44	1.55
M1-α2β3φ0	3.52	66.82	18.98	57.60	8.16	22.22	2.72	1.75
M1-α2β4φ0	3.69	84.29	22.84	67.20	8.02	39.60	4.94	2.48
M1-α2β5φ0	3.72	103.48	27.82	68.27	6.50	205.42	31.60	12.97
M1-α3β1φ0	4.01	67.64	16.87	59.37	13.13	24.50	1.87	1.41
M1-α3β2φ0	3.55	61.94	17.45	55.35	12.45	24.26	1.95	1.81
M1-α3β3φ0	3.59	76.17	21.22	61.92	12.26	30.84	2.52	2.31
M1-α3β4φ0	3.67	88.81	24.20	66.80	12.24	56.39	4.61	3.55
M1-α5β1φ0	4.11	72.81	17.72	64.94	20.30	32.87	1.62	1.91
M1-α5β2φ0	3.58	65.78	18.37	56.68	19.25	33.65	1.75	2.36
M1-α5β3φ0	3.55	82.62	23.27	63.16	19.27	43.07	2.24	3.02
M1-α5β4φ0	3.71	92.57	24.95	67.62	18.97	90.66	4.78	5.73
M1-α1β1φ-90	3.47	64.57	18.61	57.26	3.85	10.46	2.72	0.87
M1-α1β1φ45	3.78	68.31	18.07	63.32	4.14	12.91	3.12	1.33
M1-α1β1φ90	3.68	70.81	19.24	62.67	3.76	9.86	2.62	1.15
M1-α1β1φ180	3.43	67.26	19.61	60.06	4.30	11.50	2.67	1.06
M1-α2β1φ-90	3.56	63.25	17.77	57.24	8.65	15.17	1.75	0.90
M1-α2β1φ45	3.81	71.59	18.79	65.32	8.80	18.59	2.11	1.72
M1-α2β1φ90	3.79	71.78	18.94	64.10	8.82	14.39	1.63	1.48
M1-α2β1φ180	3.01	65.53	21.77	57.16	9.10	15.72	1.	1.37
M1-α3β1φ-90	3.67	66.72	18.18	59.30	13.00	23.67	1.82	1.03
M1-α3β1φ45	4.00	72.08	18.02	67.90	13.28	24.96	1.88	2.08
M1-α3β1φ90	3.62	68.55	18.94	62.45	13.39	21.16	1.58	1.68
M1-α5β1φ-90	3.70	66.19	17.89	59.47	20.02	31.63	1.58	1.20
M1-α5β1φ45	4.11	77.22	18.79	71.27	20.40	33.43	1.64	2.58
M1-α5β1φ90	3.68	68.97	18.74	62.76	20.32	29.41	1.45	2.06
M2-α0β0	10.14	52.97	5.22	8.75	0.00	4.34	—	0.19
M2-α1β0.5	10.32	55.46	5.37	9.61	10.50	15.10	1.44	1.01
M2-α1β1	10.49	58.60	5.59	9.34	10.22	32.28	3.16	1.94
M2-α1β2	10.14	57.20	5.64	9.14	10.55	12.45	1.18	0.83
M2-α2β0.5	10.12	55.40	5.47	8.74	19.41	25.36	1.31	1.66
M2-α2β1	10.67	61.27	5.74	9.61	19.17	60.80	3.17	3.73
M2-α2β2	10.08	59.62	5.91	9.77	19.40	20.78	1.07	1.32

Average displacement measured by 2 horizontal displacement gauges

Table 4-9 List of sine wave parametric excitation cases (with dampers) [42]

	Horizontal direction				Vertical direction			
	Input acceleration (Gal)	Acceleration at the top of C.B. (Gal)	Response amplification ratio	Horizontal displacement of seismic isolated base* (mm)	Input acceleration (Gal)	Acceleration at the bottom of C.B. (Gal)	Response amplification ratio	Displacement at the bottom of C.B. (mm)
M1-α0β0φ0	5.28	25.92	4.91	2.54	0.00	2.02	—	0.18
M1-α1β1φ0	5.62	26.35	4.69	11.25	7.35	10.49	1.43	0.76
M1-α1β2φ0	5.37	26.60	4.95	7.50	4.76	7.47	1.57	0.41
M1-α1β3φ0	5.27	26.27	4.98	8.82	4.90	7.29	1.49	0.52
M1-α1β4φ0	5.17	26.51	5.13	9.62	4.66	7.95	1.71	0.55
M1-α1β5φ0	5.33	28.50	5.35	13.57	6.69	9.68	1.45	0.65
M1-α2β1φ0	5.61	26.83	4.78	16.96	12.67	16.58	1.31	1.10
M1-α2β2φ0	5.24	26.82	5.12	16.02	11.55	14.63	1.27	0.83
M1-α2β3φ0	5.35	27.76	5.19	18.09	11.63	14.29	1.23	0.94
M1-α2β4φ0	5.28	30.00	5.68	20.12	11.43	14.46	1.27	1.02
M1-α3β1φ0	5.92	27.79	4.69	22.88	18.08	21.87	1.21	1.44
M1-α3β2φ0	5.25	28.07	5.35	22.05	16.68	19.38	1.16	1.13
M1-α3β3φ0	5.28	30.34	5.75	24.45	16.76	19.72	1.18	1.25
M1-α3β4φ0	5.31	30.98	5.83	27.10	16.31	19.26	1.18	1.33
M1-α1β1φ-90	5.03	25.08	4.99	10.21	5.35	7.57	1.41	0.48
M1-α1β1φ45	5.59	28.02	5.01	9.67	5.66	8.37	1.48	0.48
M1-α1β1φ90	5.44	27.47	5.05	9.28	5.55	8.21	1.48	0.43
M1-α1β1φ180	4.80	24.61	5.13	9.28	5.82	8.57	1.47	0.56
M1-α2β1φ-90	4.95	24.24	4.90	15.32	10.98	12.72	1.16	0.84
M1-α2β1φ45	5.76	28.41	4.93	15.12	11.60	14.00	1.21	0.78
M1-α2β1φ90	5.38	28.08	5.22	14.17	11.42	13.49	1.18	0.77
M1-α2β1φ180	4.67	24.88	5.33	14.91	11.33	13.81	1.22	0.92
M1-α3β1φ-90	4.85	23.99	4.95	23.32	17.51	21.31	1.22	1.18
M1-α3β1φ45	5.81	28.68	4.94	23.56	17.97	21.83	1.21	1.24
M1-α3β1φ90	5.49	28.57	5.20	21.76	17.89	21.37	1.19	1.13
M1-α3β1φ180	4.51	25.95	5.75	23.52	17.87	21.38	1.20	1.31
M2-α0β0	10.18	8.80	0.86	3.14	0.00	1.86	—	0.09
M2-α1β0.5	9.97	10	1.01	13.30	10.45	12.48	1.19	0.56
M2-α1β1	10.49	7.65	0.73	14.86	10.28	11.65	1.13	0.56
M2-α1β2	10.29	9.18	0.89	19.94	10.45	12.77	1.22	0.55
M2-α2β0.5	10.15	9.67	0.95	23.25	19.61	21.01	1.07	1.08
M2-α2β1	10.83	7.89	0.73	27.90	19.30	21.77	1.13	1.23
M2-α2β2	10.17	9.64	0.95	29.46	19.39	21.42	1.10	0.91

Average displacement measured by 2 horizontal displacement gauges

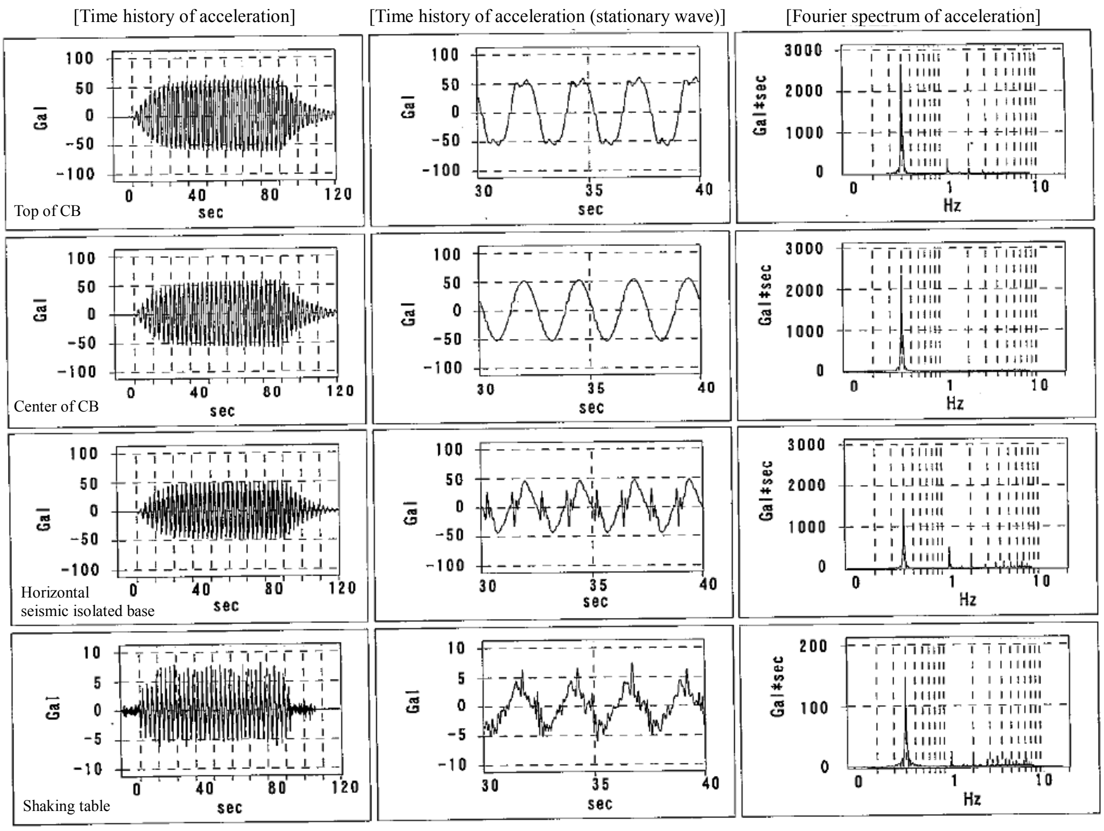


Fig. 4-29(a) Results of sine wave parametric excitation
(Without dampers: time history of horizontal acceleration) [43]

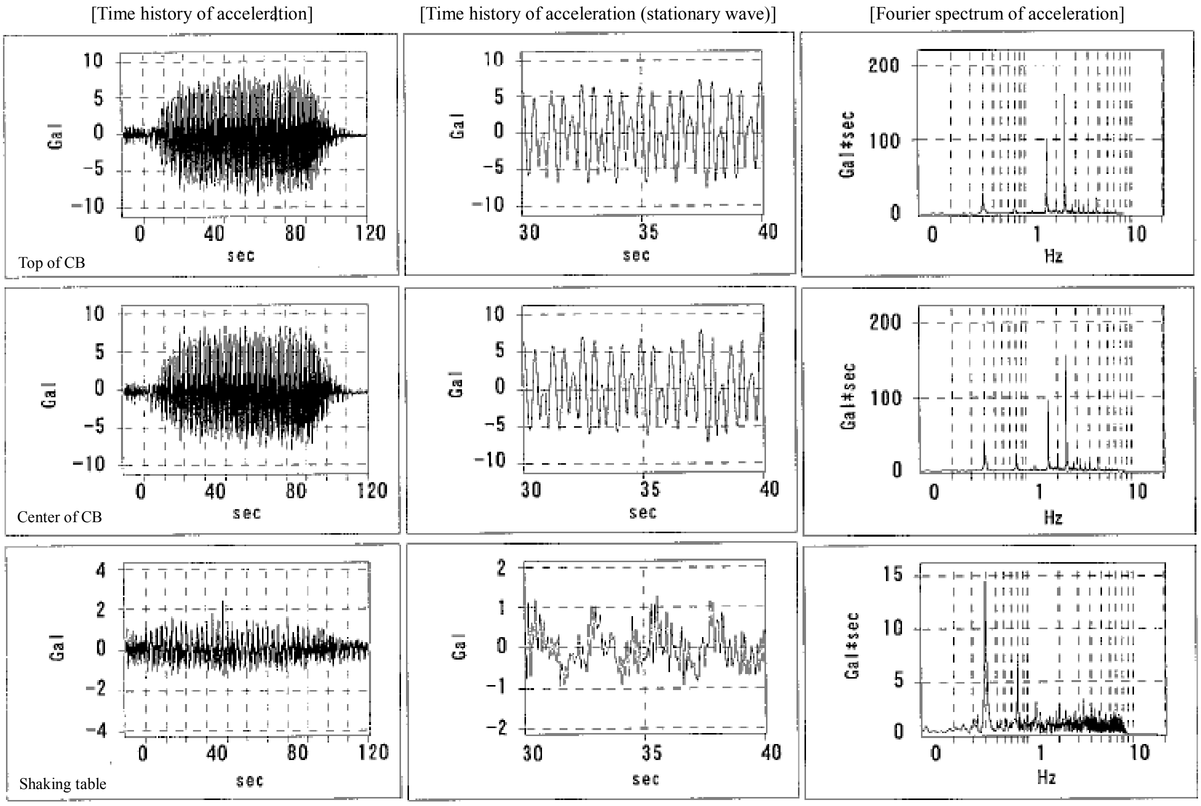


Fig. 4-29(b) Results of sine wave parametric excitation
(Without dampers: time history of vertical acceleration) [44]

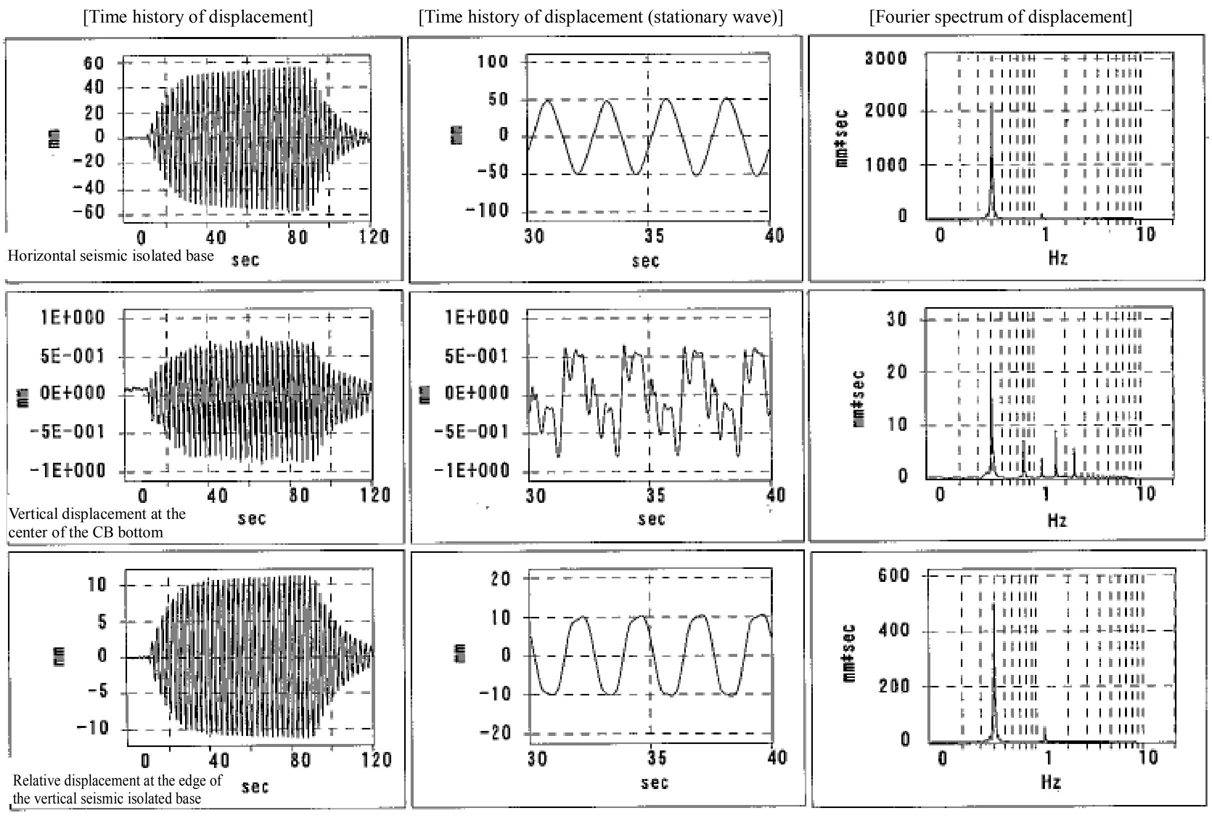


Fig. 4-29(c) Results of sine wave parametric excitation
(Without dampers: time history of displacement) [45]

2.3.5 Seismic Wave Excitation Tests and the Test Results

(1) Outline of the excitation test and the input seismic motions

In this experiment, excitation tests were performed using the seismic motion which includes various types of frequency characteristics in order to understand the seismic isolation capabilities and dynamic behavior of the 3-D seismic isolation system. Excitation tests were performed on the 3-D seismic isolation system with and without the damper, and the horizontal seismic isolation system (for comparison) with and without the damper. Three patterns were adopted for the directions of excitation: simultaneous excitation of both horizontal and vertical directions, horizontal excitation and vertical excitation. The specifications of the shaking table and the measurement method of acceleration and displacement were the same as in the sine wave sweep test.

Table 4-10 (acceleration measured on the shaking table) shows a list of input seismic waves of this test, and Fig. 4-30 shows the acceleration response spectrum (indicated by the response amplification ratio to the maximum input acceleration) of all the seismic waves. Table 4-10 shows the maximum values of acceleration and acceleration response spectrum, the acceleration response spectrum of the primary and secondary natural frequencies of the seismic isolation system and the response amplification ratio to the maximum input acceleration.

The input seismic waves are broadly divided into the seismic waves observed at JAERI’s Oharai laboratory, simulated seismic waves for design and the simulated seismic waves based on the fault model and representative strong ground motion record. Among these, EQ326-TB and EQ-326-FL are the seismic motion observed at the test field and on the first floor of the research reactor building in JAERI’s Oharai laboratory. The SID waves are the simulated seismic motion for design intended for Oharai site, while S1F waves are the improved standard waves. FM72 and FM80 are the simulated seismic motion prepared by the approach developed by Irikura and Kagawa, based on the conditions stated in Table 4-10 intended for Oharai site, assuming the magnitude 7.2 and 8.0 seismic centers in Kasumigaura fault. Each seismic waves were input after adjusting the acceleration amplitude to be within the range which gives no damage to the seismic isolation system. Also, the vertical input acceleration of S1F wave was input at half the speed of the horizontal acceleration.

The acceleration response spectrum of each input seismic wave shows the maximum value in the wide frequency band between 1.3Hz and 16Hz in horizontal direction and between 2.6Hz and 9.9Hz in vertical direction, according to Table 4-10 and Fig. 4-30. In horizontal direction, the acceleration response amplification ratios near the primary natural frequency (0.4Hz) of the seismic isolation system are at or below 0.3, except HACHINOHE wave. Thus, it is assumed that mostly good seismic isolation capability is obtained against each wave. On the other hand, in vertical direction, the acceleration response amplification ratios have a tendency to increase as much as 3 times at the maximum near the tertiary natural frequency (2.0Hz) of the seismic isolation system, except some input seismic waves such as waves observed at Oharai. Thus, extremely severe input conditions are assumed in terms of seismic isolation capabilities.

(2) Test results

As the results of the excitation tests, Table 4-12 shows the horizontal and vertical maximum response acceleration, acceleration response amplification and maximum response displacement in each excitation case of the 3-D and horizontal seismic isolation system. Fig. 4-31 and Fig. 4-32 show the comparison of the acceleration response amplification ratios and maximum response displacement in each excitation case. Fig. 4-35 and Fig. 4-34 show the ratios between the responses to the horizontal and vertical excitation and the maximum response acceleration to the simultaneous excitation in both horizontal and vertical directions. Fig. 4-16 shows the time history of acceleration and displacement responses of S1F, FM80, KOBE, EL and CENTRO waves, Fourier Spectrum and transfer functions, etc. of each part of the seismic isolation system. When obtaining the maximum responses of each part of the seismic isolation system, the time history data was filtered by the digital low pass filter to mitigate the influence of the high frequency noise of the exciter and noise of the measurement instrument. The transfer function was obtained as the acceleration Fourier spectrum ratio of the top of the shaking table smoothed by the Hanning window with the band width of 0.3Hz and each part of the seismic isolation system.

The following is the findings related to the seismic isolation capabilities and dynamic behavior of the 3-D seismic isolation system, obtained from various types of seismic wave excitation.

1) In the case of the 3-D seismic isolation system without dampers, there seems to be a tendency that the horizontal response acceleration is amplified by rocking response rather than in the case of the horizontal seismic isolation. The response is considerably amplified especially in the case of the input seismic ground motion with the dominant frequency near the horizontal secondary natural oscillation mode. Concerning the responses in vertical direction, although the response acceleration decreases in comparison to the case of the horizontal seismic isolation system, the amplification of the acceleration increases in the simulated seismic wave for design and KOBE wave where the vertical primary vibration mode and the low-frequency region are dominant. Also, considerable variation was observed in acceleration and displacement responses due to the input seismic waves.
2) In the case with dampers, the acceleration response amplification ratios in horizontal direction are generally at or below 0.5 to each seismic wave because the rocking motion was restricted by the vertical damper, and thus sufficient acceleration reduction effect was

obtained. Similarly, in vertical direction, the responses in the primary natural oscillation frequency mode considerably decrease, and the acceleration response amplification ratios were generally 1 or less. Displacement and rocking responses also considerably decrease due to the damper. These results enhanced the prospects for restricting amplification of acceleration responses against the seismic waves with various types of frequency characteristics by properly installing dampers in the seismic isolation devices.

3) When comparing the results of the simultaneous excitation in both horizontal and vertical directions and separate excitation in horizontal and vertical directions, there was no significant difference in the horizontal and vertical acceleration responses in each excitation case, and influence of simultaneous excitation (coupled effects in both horizontal and vertical directions) was hardly observed.

Table 4-10 List of characteristics of seismic waves input on the shaking table[46]

Title, direction, magnification ratio of the input seismic wave			Maximum input acceleration in horizontal direction	Acceleration response spectrum in horizontal direction *1		Maximum input acceleration in vertical direction	Acceleration response spectrum in vertical direction *1		Notes
Title of input wave	Direction	Magnification ratio to the original wave		Maximum value (Gal) [Frequency (Hz)]	Value at 0.4Hz (Gal) [Amplification ratio]		Maximum value (Gal) [Frequency (Hz)]	Value at 2.0Hz (Gal)	
EQ326-TB	NS/UD	3.00	274～298	1547 [5.31]	2.64 [0.01]	71～84	390 [4.79]	55.0 [0.65]	Waves observed at Oharai test bed
EQ326-FL	NS/UD	3.00	182～210	705 [5.89]	2.44 [0.01]	60～74	405 [5.13]	71.9 [0.97]	Waves observed at 1st floor of Oharai building
S1D	H/V	1.00	168～220	879 [6.76]	48.8 [0.29]	104～129	557 [6.76]	320 [3.04]	Design waves of Oharai site
S1F	H/0.5H	0.50	154～156	607 [3.51]	37.5 [0.24]	66～68	282 [3.51]	194 [2.91]	Improved standard waves
FM72	NS/UD	1.00	105～116	602 [1.29]	18.7 [0.16]	19～31	113 [5.5]	26.1 [1.32]	Fault model (Kasumigaura fault M7.2)
F80	NS/UD	1.00	252～263	1032 [1.33]	53.3 [0.20]	60～65	318 [2.57]	82.1 [1.38]	Fault model (Kasumigaura fault M8.0)
KOBE	EW/UD	0.33	216～221	1127 [2.57]	46.8 [0.22]	103～116	1127 [2.57]	225 [1.97]	Waves observed from strong ground motion
EL CENTRO	NS/UD	0.33～0.5	131～190	478 [16.6]	43.4 [0.31]	65～105	441 [9.89]	58.8 [0.90]	
TAFT	EW/UD	1.00	170～192	908 [2.24]	39.0 [0.22]	95～108	518 [4.32]	231 [2.13]	
HACHINOHE	EW/UD	0.33	71～74	347 [2.85]	74.1 [1.00]	33～48	231 [4.03]	82.5 [2.48]	

*1 Acceleration response spectrum of input seismic wave during excitation on the 3-D seismic isolation system without damper

Table 4-11 Conditions assumed for developing simulated seismic waves for fault model [47]

	M-7.2	M-8.0
1) Assumed site	Oharai	←
2) Assumed earthquake	Kasumigaura earthquake	←
3) Reference point	North latitude = 36.27, east longitude = 140.67 Depth = 40km	←
4) Configuration of fault	Run = N180E, inclination = 15° slide = 90°	←
5) Size of fault	Length 45km×width 40km	Length 80km×width 72km
6) Seismic moment	8.0 ×10^{19}Nm	←
7) Starting point of destruction	Running direction = south end, direction of depth = slightly deep	←
8) Asperity	Considered	←
9) Amount of stress decrement	100 bars	200 bars
10) Start-up time	1.9 seconds	4.2 seconds
11) Target maximum acceleration	100 Gals	180 Gals

Table 4-12(a) List of random excitation results (simultaneous excitation in both horizontal and vertical directions) [48]

Title of input seismic waves		Results of responses in horizontal direction						Results of responses in vertical direction							
		Without dampers			With dampers			Without dampers				With dampers			
		Maximum acceleration at the top of CB		Maximum displacement	Maximum acceleration at the top of CB		Maximum displacement	Maximum acceleration at the top of CB		Maximum displacement		Maximum acceleration at the top of CB		Maximum displacement	
		(Gal)	Amplification ratio	(mm)	(Gal)	Amplification ratio	(mm)	(Gal)	Amplification ratio	Center of CB	Edge of the table	(Gal)	Amplification ratio	Center of CB	Edge of the table
Horizontal seismic isolation	EQ326-TB	63.1	0.23	4.1	87.8	0.31	3.9	347.7	4.74	–	–	343.3	4.86	–	–
	EQ326-FL	51.0	0.24	3.3	48.8	0.27	2.8	261.6	3.91	–	–	203.7	3.39	–	–
	S1D	95.6	0.53	63.8	100.8	0.51	38.4	698.4	5.40	–	–	632.8	5.79	–	–
	S1F	88.8	0.57	50.6	55.6	0.36	20.6	367.6	5.61	–	–	492.4	7.27	–	–
	FM72	46.4	0.43	30.7	37.1	0.34	18.7	186.9	6.03	–	–	169.2	6.66	–	–
	FM80	71.2	0.27	71.0	70.6	0.28	38.4	235.9	3.79	–	–	244.7	3.75	–	–
	KOBE	102.1	0.47	78.8	85.9	0.39	40.5	309.1	3.01	–	–	422.2	3.66	–	–
	EL CENTRO	111.5	0.59	93.9	104.4	0.55	53.8	675.5	6.45	–	–	698.2	6.98	–	–
	TAFT	97.1	0.51	81.8	82.6	0.44	46.0	472.9	5.00	–	–	415.5	4.24	–	–
	HACHINOHE	65.4	0.93	69.9	40.7	0.57	33.5	181.3	4.10	–	–	247.2	5.17	–	–
3-D seismic isolation	EQ326-TB	27.3	0.09	5.7	47.2	0.16	4.1	57.2	0.72	3.5	4.1	44.7	0.53	1.3	1.4
	EQ326-FL	18.2	0.10	4.2	24.0	0.11	3.4	72.1	1.03	4.5	5.4	38.2	0.51	1.2	1.5
	S1D	150.0	0.68	52.3	66.5	0.39	36.5	424.2	4.08	26.4	31.6	93.3	0.89	4.4	8.2
	S1F	123.9	0.80	38.9	46.2	0.30	18.4	242.5	3.60	15.0	20.4	69.1	0.89	2.3	4.5
	FM72	151.4	1.44	24.5	52.3	0.45	15.5	34.1	1.81	2.4	7.6	19.4	0.98	1.0	3.3
	FM80	209.3	0.82	50.3	94.1	0.36	31.0	80.1	1.32	5.0	11.4	58.5	0.98	2.3	5.8
	KOBE	307.9	1.41	73.7	106.4	0.49	27.8	234.2	2.08	14.6	25.3	94.4	0.83	5.0	9.0
	EL CENTRO	114.2	0.87	46.8	61.0	0.44	28.8	62.6	0.95	13.4	19.7	38.3	0.59	1.2	4.9
	TAFT	184.8	1.09	46.7	86.5	0.48	30.0	256.7	2.46	15.8	18.8	97.7	0.90	3.8	6.4
	HACHINOHE	138.3	1.95	84.8	57.3	0.78	33.4	71.5	2.13	4.4	10.2	42.0	1.26	1.0	5.2

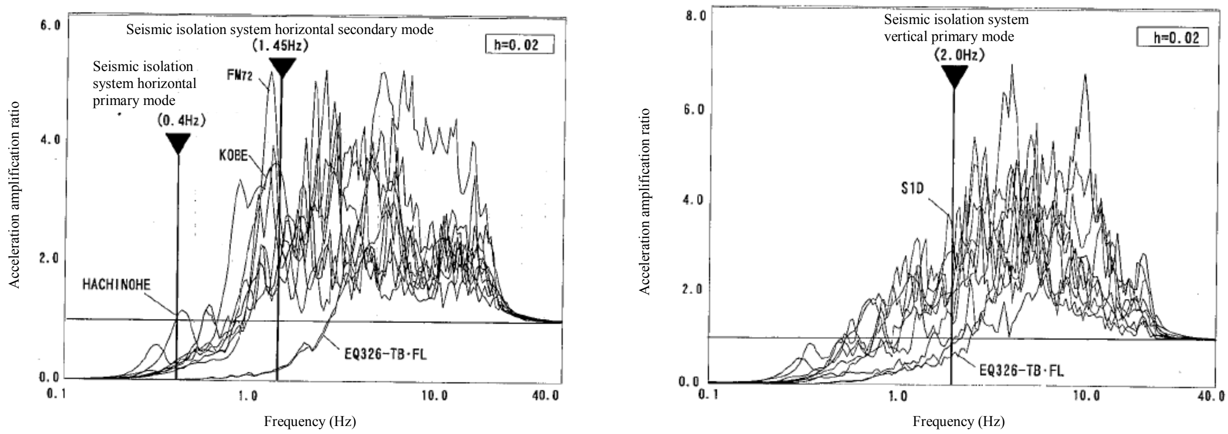
Table 4-12(b) List of random excitation results (3-D seismic isolation system, excitation in horizontal direction) [49]

		Results of responses in horizontal direction				Ratio of simultaneous excitation/horizontal excitation		Results of responses in vertical direction			
		Maximum input acceleration (Gal)	Maximum acceleration at the top of CB		Maximum displacement	Maximum acceleration at the top of CB	Maximum displacement	Maximum input acceleration (Gal)	Maximum acceleration at the top of CB	Maximum displacement	
			(Gal)	Amplification ratio						Center of CB	Edge of the table
Without dampers	EQ326-TB	299.8	25.1	0.08	5.15	1.1	1.125	3.8	3.3	0.3	1.1
	EQ326-FL	179.6	18.1	0.10	3.9	0.97	1.035	3	2.3	0.2	0.8
	S1D	184.1	138.3	0.75	48.6	0.91	0.9	5.3	27.7	2.6	9.8
	S1F	158.5	109.3	0.69	42	1.15	0.94	3.5	17.7	1.3	6.2
	FM72	103.1	157.1	1.52	24.2	0.95	0.995	3.3	17.9	1.5	7.9
	FM80	252.7	203.1	0.80	50.8	1.01	0.975	4.8	37.9	2.9	11
	KOBE	214.3	302.1	1.41	88.45	1	1.08	5.2	54.3	3.9	12.8
	EL CENTRO	131.7	130.6	0.99	48.6	0.91	0.965	4.1	30.9	2.4	9.9
	TAFT	159.4	148.7	0.93	46.05	1.18	0.95	5.5	32.3	1.9	9.9
	HACHINOHE	74.7	130.5	1.75	84.3	1.12	1.06	4	14.4	1.2	8.9
With dampers	EQ326-TB	298.7	38.9	0.13	4.2	1.27	0.96	3.2	6.2	0.5	0.1
	EQ326-FL	218.8	23.5	0.11	3	1.06	1.185	2.5	5.2	0.5	0.1
	S1D	180.4	65.1	0.36	38.1	1.09	1.025	6	8.8	4.7	0.5
	S1F	151.3	45.3	0.30	18.2	1.01	0.995	3.7	5.4	3	0.3
	FM72	113.7	51.8	0.46	15.05	1.01	1.005	2.5	4.3	3.2	0.3
	FM80	281.3	92.7	0.33	30.6	1.01	1.01	4.9	8.4	5.7	0.5
	KOBE	217.9	111.1	0.51	27.6	0.97	1.02	4.4	9.7	5.8	0.8
	EL CENTRO	135.6	60.6	0.45	28.55	0.98	0.985	2.9	7.2	5.1	0.3
	TAFT	170.5	80.5	0.47	30.45	1.01	0.93	5.8	9.7	5.8	0.5
	HACHINOHE	74.3	57.2	0.77	33.35	1.01	1.005	3.1	5.9	5	0.3

Table 4-12(c) List of random excitation results

(3-D seismic isolation system, excitation in vertical direction) [50]

	Results of responses in horizontal direction			Results of responses in vertical direction					Ratio of simultaneous excitation/horizontal excitation		
	Maximum input acceleration (Gal)	Maximum acceleration at the top of CB	Maximum displacement (mm)	Maximum input acceleration (Gal)	Maximum acceleration at the top of CB		Maximum displacement (mm)		Maximum acceleration at the top of CB	Maximum displacement	
					(Gal)	Amplification ratio	Center of CB	Edge of table		Center of CB	Edge of table
EQ326-TB	3.9	4.4	0.15	77.1	47.3	0.61	1.4	1.3	1.03	1.09	1.09
EQ326-FL	3.9	4.5	0.1	71.9	40.7	0.57	1.2	1.1	0.97	1.13	1.30
S1D	9.5	8.7	0.5	105.8	93.9	0.89	4.4	4.3	0.99	1.02	1.85
S1F	3.3	4.5	0.1	67.5	58.9	0.87	2.6	2.3	0.99	0.99	1.71
FM72	3.4	3.7	0.1	18.8	22.7	1.21	0.8	0.8	0.90	1.32	4.34
FM80	4.1	4.5	0.1	59	58.2	0.99	2.4	2.4	1.02	0.97	2.45
KOBE	5.5	8	0.2	109.4	98.9	0.90	5.3	5.1	0.99	1.02	1.77
EL CENTRO	5.3	5.4	0.1	62.8	37	0.59	1.3	1.3	1.09	0.96	3.93
TAFT	3.1	4.8	0.1	108.4	97.7	0.90	3.9	3.9	1.00	0.97	1.64
HACHINOHE	3.3	4	0.1	36.2	35.7	0.99	1.1	1.1	1.08	0.84	4.35



【Horizontal direction】 【Vertical direction】

Fig. 4-30 Input seismic waves and acceleration response spectrum[51]

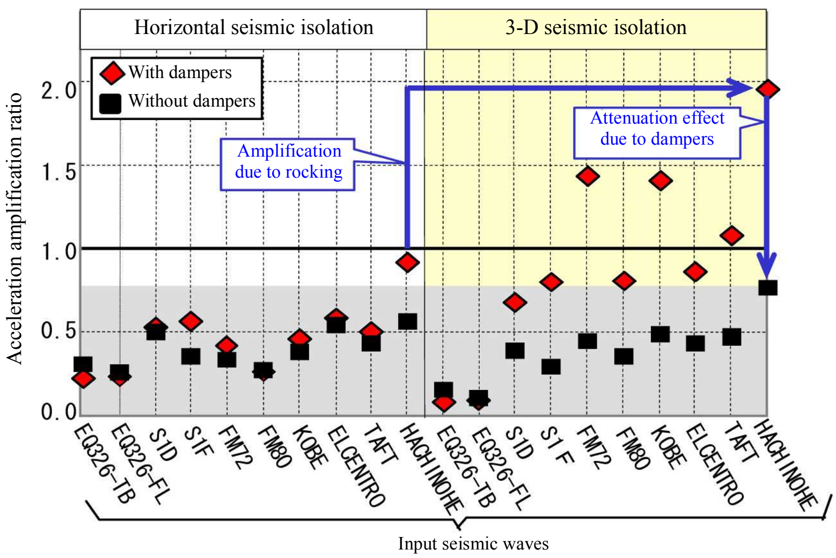


Fig. 4-31 Horizontal acceleration amplification ratio to each input seismic wave [52]

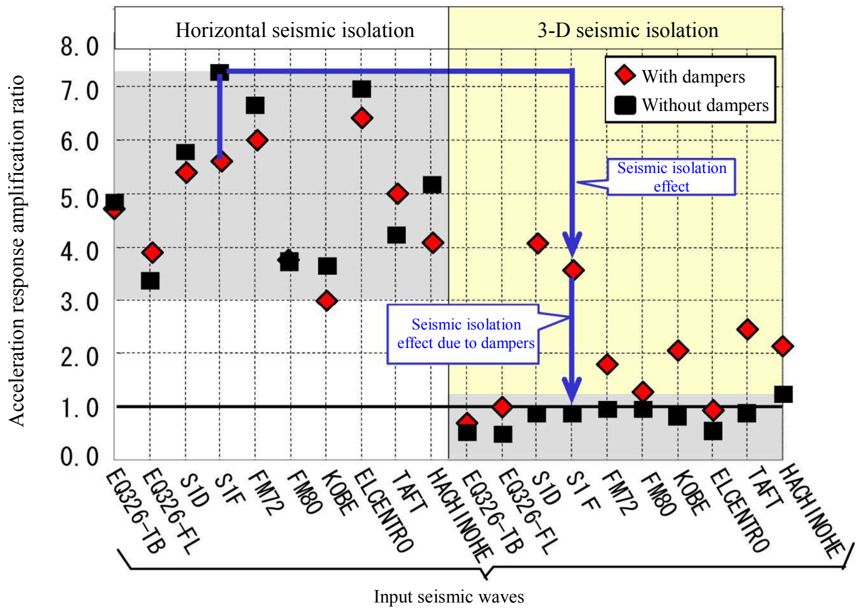


Fig. 4-32 Vertical acceleration amplification ratio to each input seismic wave[53]

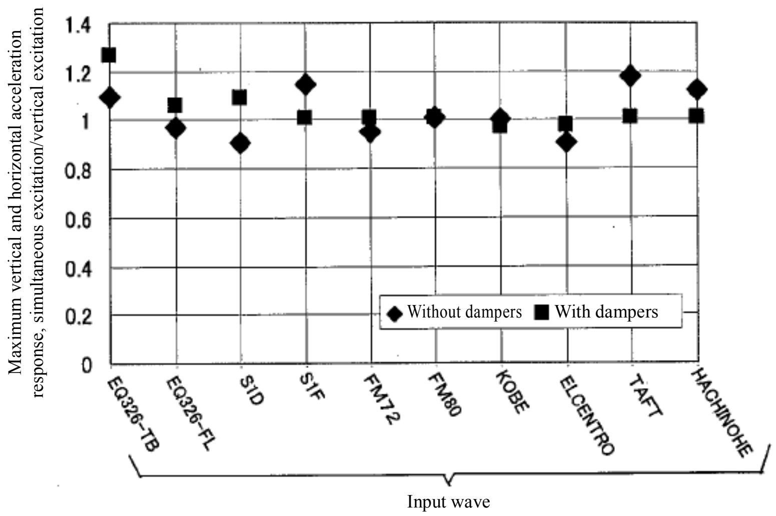


Fig. 4-33 3-D seismic isolation system, acceleration response ratio of horizontal excitation in comparison to simultaneous excitation[54]

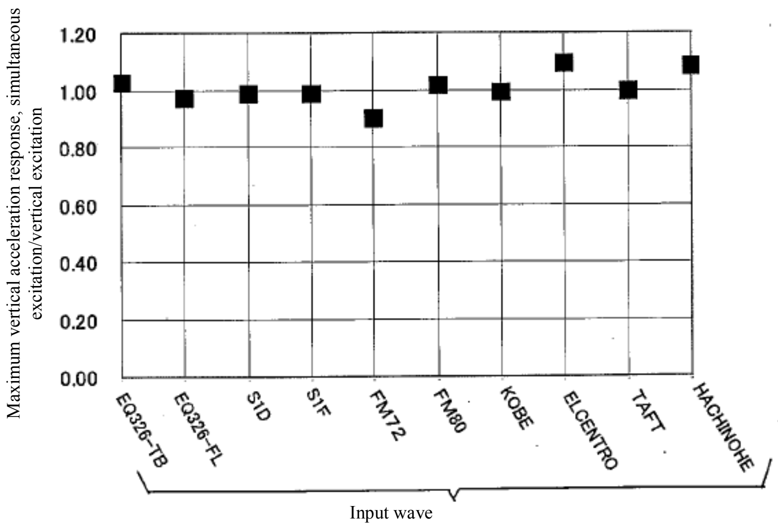


Fig. 4-34 3-D seismic isolation system (with dampers), acceleration response ratio of vertical excitation to simultaneous excitation[55]

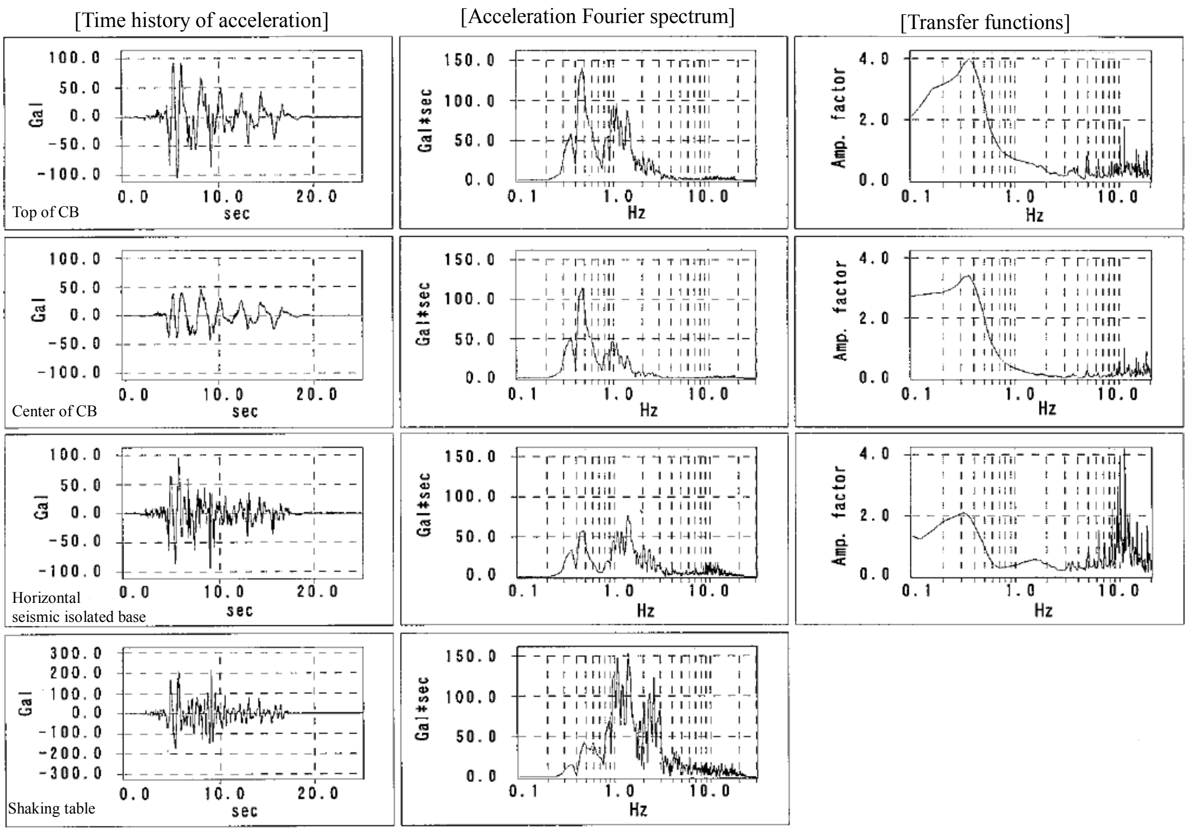


Fig. 4-35(a) Results of random excitation to the 3-D seismic isolation system with dampers (KOBE/horizontal response acceleration) [56]

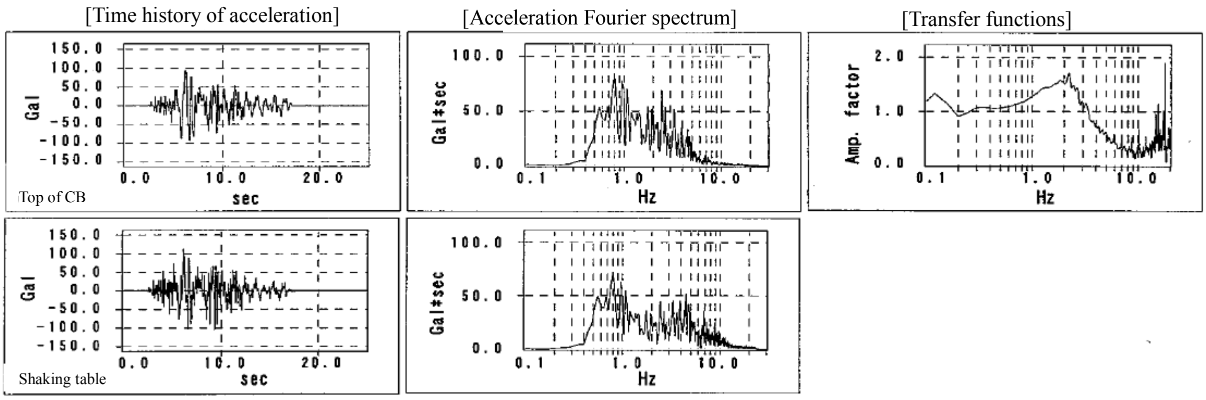


Fig. 4-35(b) Results of random excitation to the 3-D seismic isolation system with dampers (KOBE/vertical response acceleration) [57]

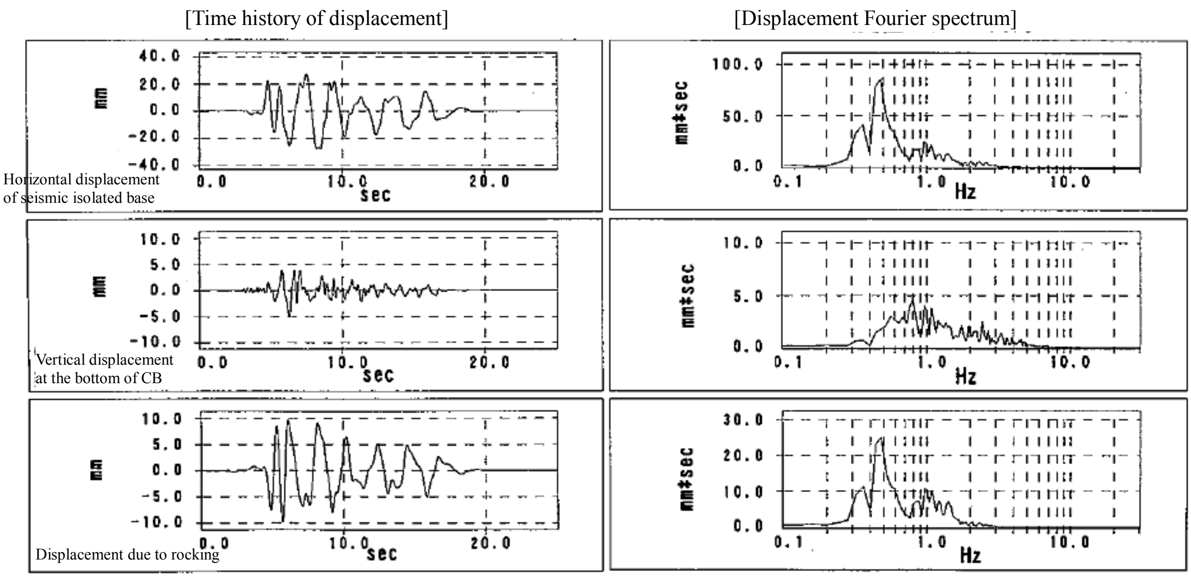


Fig. 4-35(c) Results of random excitation to the 3-D seismic isolation system with dampers (KOBE/ response displacement) [58]

[1] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.3, Fig. 2.1.1] : Reprint
[2] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.8, Fig. 2.2.1] : Reprint
[3] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.9, Fig. 2.2.2] : Reprint
[4] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.10, Fig. 2.2.3] : Reprint
[5] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.12, Fig. 2.3.1] : Reprint
[6] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.15, Fig. 3.2.1] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.16, Picture 3.2.1] : Reprint
[7] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.17, Fig. 3.2.2] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.18, Picture 3.2.2] : Reprint
[8] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.19, Fig. 3.2.3] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.20, Fig. 3.2.3] : Reprint
[9] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.21, Fig. 3.2.4] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.22, Picture 3.2.4] : Reprint
[10] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.25, Fig. 3.3.1(b)] : Reprint
[11] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.26, Fig. 3.3.2(b)] : Reprint
[12] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.27, Fig. 3.3.3] : Reprint
[13] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.27, Fig. 3.3.4(b)] : Reprint
[14] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.29, Fig. 3.3.6] : Reprint
[15] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.30, Fig. 3.3.7] : Reprint
[16] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.39, Fig. 4.1.1] : Reprint
[17] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.42, Table 4.2.1] : Reprint
[18] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.43, Fig. 4.2.1(a)] : Reprint
[19] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.44, Fig. 4.2.1(b)] : Reprint
[20] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.45, Fig. 4.2.1(c)] : Reprint
[21] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.60, Fig. 5.1.2] : Reprint
[22] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.65, Table 5.3.1] : Reprint
[23] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.66, Fig. 5.3.1(a)] : Reprint
[24] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.67, Fig. 5.3.1(b)] : Reprint
[25] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.68, Fig. 5.3.1(c)] : Reprint
[26] [Hideaki, T., *et al*., JAERI-Tech 2000-086, (Japan Atomic Energy Research Institute, February 2001), p.69, Fig. 5.3.1(d)] : Reprint
[27] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.5, Fig. 2.1] : Reprint
[28] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.5, Fig. 2.2] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.6, Picture 2.1] : Reprint
[29] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.8, Fig. 2.3] : Reprint

[30] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.16, Table 3.1] : Reprint
[31] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.15, Fig. 3.1] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.15, Picture 3.1] : Reprint
[32] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.16, Fig. 3.2] : Reprint
[33] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.17, Table 3.3] : Reprint
[34] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.17, Fig. 3.3] : Reprint
[35] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.24, Table 3.4] : Reprint
[36] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.18, Fig. 3.4] : Reprint
[37] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.18, Fig. 3.5] : Reprint
[38] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.19, Fig. 3.6] : Reprint
[39] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.29, Fig. 4.1(a)] : Reprint
[40] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.30, Fig. 4.1(b)] : Reprint
[41] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.31, Table 4.2] : Reprint
[42] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.32, Table 4.3] : Reprint
[43] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.33, Fig. 4.1(a)] : Reprint
[44] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.34, Fig. 4.1(b)] : Reprint
[45] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.35, Fig. 4.1(c)] : Reprint
[46] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.63, Table 5.1] : Reprint
[47] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.63, Table 5.2] : Reprint
[48] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.67, Table 5.3(a)] : Reprint
[49] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.68, Table 5.3(b)] : Reprint
[50] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.69, Table 5.3(c)] : Reprint
[51] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.66, Fig. 5.2(a)] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.66, Fig. 5.2(b)] : Reprint
[52] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.69, Fig. 5.3] : Reprint
[53] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.69, Fig. 5.4] : Reprint
[54] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.71, Fig. 5.7] : Reprint
[55] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.71, Fig. 5.8] : Reprint
[56] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.84, Fig. 5.15(a)] : Reprint
[57] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.85, Fig. 5.15(b)] : Reprint
[58] [Hideaki, T., *et al*., JAERI-Tech 2001-033, (Japan Atomic Energy Research Institute, June 2001), p.85, Fig. 5.15(c)] : Reprint

Appendix-1

Examples of Implementation of Seismic Isolation Device in Response to Needs and Other Factors Pertaining to Seismic Isolation Structure

Examples of Seismic Isolation Device Implementation:

<table>
<tr><th colspan="2">Type of Base-Isolation Structure</th><th>Seismic Isolation Device (restoring function)</th><th>Direction of Seismic Isolation</th><th>Plant status</th></tr>
<tr><td colspan="2" rowspan="2">Building Isolation</td><td>Rubber elements</td><td>Horizontal (*1)</td><td rowspan="2">New plant (*2)</td></tr>
<tr><td>Rubber elements</td><td>Horizontal
Vertical</td></tr>
<tr><td rowspan="2">Equipment Isolation</td><td>Seismic isolation of heavy equipment (*3)</td><td>Rubber elements
Mechanical elements</td><td>Horizontal
Vertical</td><td>New plant
Existing plant</td></tr>
<tr><td>Seismic isolation of light equipment (*4)</td><td>Mechanical elements</td><td>Horizontal
Vertical</td><td>New plant
Existing plant</td></tr>
</table>

*1: Combination of different types of base-isolation are available, for example; the combination of the building isolation in horizontal direction and the equipment isolation in vertical direction for components which are vulnerable to vertical motion.

*2: In the case where emergency diesel generators are seismically isolated, both the equipment isolation for the diesel generators and the building isolation for new building in which the diesel generators are installed are available.

*3: Heavy equipment generally refers to equipment that weighs more than about 100 tons (e.g. emergency diesel generator).

*4: Light equipment generally refers to equipment that weighs less than about 100 tons (e.g. electrical gear).

Appendix-2

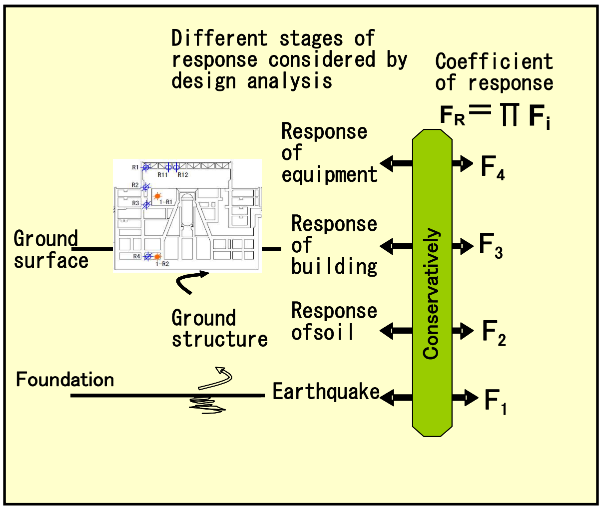
Notes on Seismic Safety Margin of Base-Isolated Structure

(1) Features of base-isolated structure from the viewpoint of seismic safety margin

The seismic safety margin is defined as a distance between response and seismic capacity. The seismic safety margin of base-isolated structures has the following features:

(Response of base-isolated structure)

The gross response factor can be broken down into four components, F1 through F4, as illustrated below.



F1: Response factor related to the ground motion

F2: Response factor related to propagation of the ground motion

F3: Response factor related to building

F4: Response factor related to component

- F1 (Response factor related to the ground motion)

  Base-isolated structures have a relatively long natural period. For the creation of design basis ground motion, the uncertainty of longer period components is believed to be smaller than that of short period components.

- F2 (Response factor related to propagation of the ground motion)

  Considering that nuclear power generation facilities are normally built on solid ground structure, it is believed that the uncertainty of longer period components, which affect response of the base-isolated structure, is generally small.

- F3 (Response factor related to building)

  -- Aeismic building

  Since the dominant natural period of building is shorter than 0.5 seconds, the transferred seismic motion through the building is expected to have only a minor effect on the response of equipment isolation whose natural period is around 2 seconds.

-- Base-isolated building

Since the behavior of the base-isolated structure during earthquake is relatively simple and the characteristics of the seismic isolation device can be confirmed by product testing, etc., the uncertainty of response of the base-isolated building is small.

- F4 (Response factor related to component)
    - Isolated equipment

      For a reason similar to the one given above for base-isolated building, the uncertainty of response of the equipment is small.
    - Non-isolated equipment

      The uncertainty of response of equipment in the base-isolated building is small. This is because of small uncertainty of the response of the base-isolated building and a large difference of the natural period between building and equipment.
- The small uncertainty of the response of base-isolated structures suggests that the extra-design safety margin of the response could be smaller in the base-isolated structures than that in the non-isolated structures.

(Seismic capacity of base-isolated structure)

- The seismic capacity of the base-isolated structure may be determined by physical conditions such as the clearance between base-isolated and on-isolated structure or, in the case of equipment isolation, the movable displacement of damper, for example. In such instances, the extra-design safety margin for seismic capacity could be smaller in the base-isolated structures than that in the non-isolated structures.

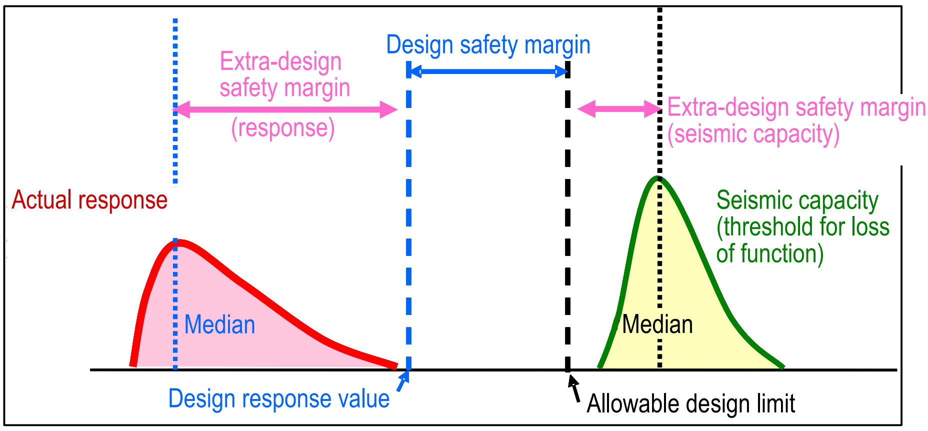


Illustration of the concept of seismic safety margin

(2) Seismic safety margin of the base-isolated structure

- Even though the ground motion observed at the Niigata-ken Chuetsu-oki Earthquake extremely exceeded the design basis, it did not cause damage to any system, structures and components (SSCs) important to safety.
- It should be mostly because of a large seismic safety margin of SSCs including both design safety margin and extra-design safety margin.
- However, as mentioned above, the base-isolated structure may have less extra-safety margin than the non-isolated structure because they are more likely to "respond as predicted" and "fail as predicted."
- Remembering that the Regulatory Guide for Reviewing Seismic Design describes "every effort should be made, at the design of the facilities to minimize the "residual risks" to the extent as low as practically possible", utilities are encouraged to design considering sufficiently large safety margin and choose a conservative approach to the determination of the design basis ground motion.

(3) Measures for the securing of the seismic safety margin

- In the case of the base-isolated structure, relative displacement caused by earthquake is larger than the case of the non-isolated structure. Therefore, crossover piping, etc., between base-isolated and non-isolated structure/component often becomes a cause of critical seismic safety concern. It is advisable to ensure sufficient design margin by taking measures such as the strategic routing of piping, and the use of expansion joints.
- The use of a fail-safe mechanism could be one of the measures that can be taken to ensure protection against the beyond-the-design-basis ground motion and various types of the fail-safe mechanisms have been invented. Even though the development and deployment of the fail-safe mechanism should continue to be promoted in the future, it would not be appropriate to have utilities implement such mechanisms as an obligation imposed by a regulatory requirement. The use of the fail-safe mechanisms, therefore, is left up to the discretion of utilities.

Appendix-3

Overview of Seismic PSA

The following provide an overview of seismic PSA and major precautions:

(Seismic hazard evaluation)

- Since seismic hazards are site-specific regardless of the presence or absence of seismic isolation structures, utilities may seek compliance with “Standard for Procedure of Seismic Probabilistic Safety Assessment for Nuclear Power Plants” by the Atomic Engineering Society of Japan. (AESJ S-PSA Procedure Standard)
- Since the seismic isolation structures have a long natural period, the seismic hazard assessment performed for the seismic isolation structures should be evaluated in consideration of long period components of ground motion.

(Fragility evaluation)

- Utilities may seek compliance with AESJ S-PSA Procedure Standard which also prescribes fragility evaluation methods for building isolation and equipment isolation.
- The data specific to seismic isolation structures, such as uncertainty of seismic isolation elements are not provided by AESJ S-PSA Procedure Standard. It is expected that such kinds of data would become available in the future by the progress of researches.

(Accident sequence evaluation)

- Since the evaluation of accident sequences does not depend on the presence or absence of seismic isolation structures, utilities may seek compliance with AESJ S-PSA Procedure Standard.

Appendix-4

Aging of Seismic Isolation Device

- When the seismic isolation structure is implemented at nuclear power facilities, the seismic isolation device, either for building isolation or for equipment isolation, is normally placed in a controlled environment. Therefore, it is expected that the seismic isolation device relatively well protected against the aging.
- Nevertheless, it can't be denied that the characteristics of the seismic isolation device would change due to external forces from the load of the superstructure and from earthquake, for example, or due to external environmental factors such as moisture and dust.
- The following lists topics requiring attention in connection with the aging of seismic isolation device:
  (i)Identification of causes that determine the durability of the materials composing the seismic isolation device
    - By available knowledge on the durability of seismic isolation device and by conducting durability tests, for example, utilities should identify the external factors, such as environmental conditions, that contribute to the aging of various materials composing seismic isolation device and try to study the methods for the prediction of how characteristics, such as rigidity and damping capability, change due to aging.

  (ii) Quantification of the external factors such as environmental conditions
    - Quantitatively determine the influence of external factors, such as environmental conditions, that have impacts on the durability of seismic isolation device.

  (iii) Predicting the aging of seismic isolation device
    - Predict how the characteristics of seismic isolation device will change during the in-service period due to the influence of external factors expected under the environmental conditions to which the seismic isolation device is exposed.

  (iv) Design of the seismic isolation device in consideration of aging
    - Design the seismic isolation device in consideration of the change of characteristics predicted in the step above.

  (v) Inspection, repair and replacement after completion of construction
    - Upon completion of seismic isolation device, take measurements of initial values which serve as the baseline in in-service inspections.
    - Seismic isolation device should be designed to replaceable as needed.
- Factors that may contribute to aging depend on the configuration of seismic isolation device. Therefore, the identification of factors contributing to aging shall be done in consideration of the type of seismic isolation device and its particularities. It is also

important to remember that seismic isolation device remains inactive under normal condition.

- The following are typical examples of factors that contribute to the aging:
  - (i) Stiffness providing mechanism
    - Spring: rusting.
    - Laminated rubber bearing: rusting and hardening.
  - (2) Dead weight supporting mechanism
    - Ball bearing: adhesion, deterioration, leakage of lubricant and scars caused by the ball contacts with the supporting steel plate at fixed positions.
    - Ball bearing supporting steel plate: rusting and indentation.
    - Laminated rubber bearing: creep.
  - (iii) Damping mechanism
    - Oil dampers: deterioration, leakage and separation of oil.
    - Steel dampers: rusting.
    - Friction dampers: rusting.