February 17, 2000

Ronald W. Hernan
Division of Licensing Project Management
U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
11555 Rockville Pike, OWFN-8G9
Rockville, MD 20852-2738

Subject: SQUG Procedure for Gathering and Validating Earthquake Experience Data, Revision 1

Dear Mr. Hernan:

Enclosed for your review and approval is Revision 1 of the Procedure for Gathering and Validating Earthquake Experience Data. This enclosure is the second of the two procedures which the NRC requested for review and approval on page 9 of SSER No. 2 for the GIP which was transmitted by GL 87-02, Supplement 1. The first procedure, on how the GIP would be revised using new information including earthquake experience data, was submitted by SQUG on May 22, 1997, and approved by the NRC in SSER No. 3 on December 4, 1997. The second procedure, on gathering and validating earthquake experience data, was originally submitted to the NRC by SQUG on December 19, 1996. The NRC prepared a Request for Additional Information (RAI) on this second procedure and sent it to SQUG on May 12, 1997. A follow-up meeting between NRC staff and SQUG representatives was held on November 29, 1999, to discuss the proposed revision to this second procedure. This letter forwards Revision 1 of this second procedure as a deliverable of the generic SQUG program effort.

Enclosure 1 contains SQUG's responses to the comments and questions contained in the RAI sent to SQUG on May 12, 1997, on the "Procedure for Gathering and Validating Earthquake Experience Data." Enclosure 2 is Revision 1 of this procedure which incorporates SQUG responses to the RAI and also the suggestions discussed during the SQUG/NRC meeting on November 29, 1999. The principal issues raised in the RAI and our response to them are summarized below.

One of the general comments made in the RAI was that there is a distinction between (1) the process of collecting and validating earthquake experience (EE) data and (2) the uses to which these data may be put for evaluating the seismic adequacy of equipment. We agree that there is a distinction and have revised the enclosed procedure to address only the process of collecting and validating EE data.

YE01
ADD: Ron Hernan
to eRIDS

Rec'd at DCD from
Ron Hernan on
9/25/00.

Another issue discussed in several places in the RAI was the adequacy of the ground motion estimates at the database sites. The procedure has been revised to describe how a ground-motion response spectrum at an individual database site would be determined depending on the number and location of strong-motion recordings that are available from the earthquake that affected the site. An appendix with three examples has also been added to the procedure to illustrate how this process can be used to estimate ground response spectra at database sites.

Finally, the RAI asked that material be submitted which shows how the raw data was compiled into the earthquake experience database. In response to this request, a copy of the SQUG Electronic Earthquake Experience Database was submitted in a separate letter to the NRC (P.Y. Chen) from EPRI (R. Kassawara) dated May 19, 1998. That letter forwarded a set of two CD-ROMs (Electronic Database WINSQUG V2.0) and a user's guide for operating the database manager (EPRI Technical Report TR-110781).

Although a copy of the SQUG Electronic Earthquake Experience Database was sent to the NRC, as described in the preceding paragraph, we are not asking that it be reviewed and approved. This database was sent simply to provide the NRC staff with reference material to enable them to understand the framework of the database into which new information will be placed as it is gathered and validated using the enclosed procedure. We ask, however, that the NRC review and approve the process defined in the enclosed Procedure for Gathering and Validating Earthquake Experience Data. Completion of your review and approval by May 2000 would be appreciated to facilitate use of the procedure by SQUG members.

After the enclosed procedure is reviewed and approved, SQUG intents to use it to gather and validate earthquake experience data and add these data to the SQUG Electronic Earthquake Experience Database. Use of this procedure will result in a burden reduction for both the NRC and the utilities. The NRC's burden will be reduced because it will be unnecessary for the NRC staff to review and approve ground motion estimates and EE data as they become available, except as may be necessary to occasionally audit the implementation of this procedure. Utilities will also experience a burden reduction since they will be able to pool their resources through the use of a NRC-reviewed and approved procedure to gather and validate EE data. This will also promote a consistent approach to collecting these data. Another burden reduction which utilities will realize is not having to prepare submittals each time new data become available. Instead, the review and approval process included in the enclosed procedure will serve to ensure that new data are of high quality.

Sincerely,

Neil P. Smith

Neil P. Smith, Chairman
Seismic Qualification Utility Group

Enclosures:

(1) Detailed Responses to NRC Comments
(2) Procedure for Gathering and Validating Earthquake Experience Data, Revision 1

cc: R. Wessman, NRC/NRR, OWFN-7D26
E. Imbro, NRC/NRR, OWFN-7E23
K. Manoly, NRC/NRR, OWFN-7E23
R. Rothman, NRC/NRR, OWFN-7E23
P.Y. Chen, NRC/NRR, OWFN-7E23
SQUG Steering Group
SQUG Representatives

Enclosure 1 to
SQUG Letter Dated
February 17, 2000

DETAILED RESPONSES TO NRC COMMENTS

The purpose of this enclosure is to provide the Seismic Qualification Utility Group (SQUG) response to each of the comments in the Nuclear Regulatory Commission (NRC) Request for Additional Information (Reference 1.) The NRC comments are in *italics*, followed by the SQUG response.

REFERENCES

(1) NRC (J. Stolz) Letter to SQUG (N. Smith), dated May 12, 1997, "Request for Additional Information Regarding the Seismic Qualification Utility Group (SQUG) Procedure for Evaluating the Acceptability of New Earthquake Experience Data (TAC No. M40580)

(2) Bandyopadhyay, K.K., et. al., "An Evaluation of Methodology for Seismic Qualification of Equipment, Cable Trays, and Ducts in ALWR Plants by Use of Experience Data," NUREG/CR-6464, July, 1997.

(3) Yanev, P.I. and Swan, S.W., "Program for the Development of an Alternative Approach to Seismic Equipment Qualification, " Vols. 1 and 2, September, 1982.

(4) Chang, T.Y., "Seismic Qualification of Equipment in Operating Nuclear Power Plants, " NUREG-1030, February, 1987.

(5) EPRI (R. Kassawara) Letter to NRC (P. Chen), dated May 19, 1998, "TR-110781, Rev. 0, 'SQUG Electronic Earthquake Experience Database User's Guide,' May, 1998, and the Electronic Database WINSQUG V2.0 (set of two CDROMs)."

(6) Seismic Qualification Utility Group Newsletter, Volume 2, Issue 2, June 1994.

(7) Seismic Qualification Utility Group Newsletter, Volume 3, Issue 2, September 1995.

GENERAL COMMENTS

In general, there should be two separate procedures for providing an acceptable, well-controlled document on the use of earthquake experience data for any purpose:

I. The procedure for the establishment of an earthquake experience database; and

II. The procedure for screening, assessing, and applying the earthquake experience database.

SQUG's December 19, 1996, submittal, entitled "Gathering and Validating New (Post 1985) Earthquake Experience Data" is to address the first procedure stated above. With respect to the second procedure, for USI A-46 purposes, SQUG has developed GIP-2, and for the purpose of future seismic qualification of equipment, the industry is developing a "First of a Kind Engineering" (FOAKE) procedure. The staff has not reviewed the FOAKE procedure. In the resolution of the USI A-46 program, although the staff has approved the use of GIP-2 with some restrictions, the staff has not reviewed the details or approved the earthquake experience database, contrary to SQUG's statement in Section 1.0 (Purpose). SQUG's December 19, 1996, submittal, seems to contain both Procedures (I) and (II), although the title of the submittal is for Procedure (I) only. Therefore, the staff will review the information concerning Procedure (I) and will review only the areas in Procedure (II) that are pertinent to USI A-46 applications.

SQUG agrees with this comment. The procedure has been revised to remove references to use of the data. However, we would like to provide clarification on use of the data. Use of the data can be put into three areas: a) use of the GIP for USI A-46, which was reviewed and approved by NRC; b) use of the GIP for new and replacement equipment (NARE guidelines were reviewed by NRC); and c) specific verification activities which must be justified on a case by case basis by the licensee.

Although the staff has no intention to review any areas relating to the FOAKE project applications at this time, we noted, however, on Page 8 in Section 4.6.2 of the referenced SQUG's submittal, your statement that "A detailed review, including independent estimates of ground motion at the Reference sites, was prepared by David Boore of USGS..." We note that, of the 25 sites for which Boore prepared estimates, his estimate of the average spectral acceleration in the frequency range of 3 to 8 Hertz for 14 of the sites is less than that of the FOAKE Project Team estimates. Potentially, your statement could be subjected to misinterpretation and could lead to the assumption that Boore agreed with the FOAKE Project Team estimates.

We agree that the NRC should not review the FOAKE project. The FOAKE project was a special case related to criteria for advanced reactor design only, and it was not intended as the industry guideline for use of earthquake experience data. Our statement in the original procedure was based on the last paragraph of Section 2.2.4 of Reference 2, which states, "The ground motion estimates of past earthquake events for which equipment performance data were used by ARC have been independently verified by a consultant to the Panel and found to be reasonable." The consultant, David Boore, was selected by NRC. This section on FOAKE Peer Review has been deleted from the procedure.

For the earthquake experience-based approach, in the collection of the database information, one needs to define the characteristics of the actual earthquake and input motion to the equipment, the dynamic characteristics of equipment, and resulting performance of the equipment. Sufficient information of this kind, when compiled and evaluated, will then serve as a basis for qualifying a candidate equipment by satisfying excitation and physical similarity principles.

It was SQUG's intention in establishing the database of earthquake experience to collect the same level of information that was contained in Reference 3. This level of information was reviewed and found sufficient for the earthquake experience-based approach in NUREG-1030 (Reference 4). The additional details referred to which would be desirable for

1:1 equipment qualification are not required to show representation if the equipment is in one of the GIP equipment classes.

The database equipment items should have been closely inspected post-earthquakes. Their seismic responses should have been adequately estimated and evaluated based on the information collected at the site. Any equipment damages caused by the earthquake should have been recorded in detail. Any equipment malfunction or anomalies that occurred during and after the earthquake should also have been documented, with the root causes properly evaluated. These damages and anomalies, when compiled and evaluated, are essential in establishing the caveats and in applying the excitation and physical similarity principles for the qualification of each equipment class or individual equipment items.

We agree with this statement. SQUG has compiled the database following the precedent of Reference 3, which was found acceptable for demonstrating the feasibility of the earthquake experience-based approach in Reference 4. This same level of information gathering was continued in expanding the initial database to establish the equipment class descriptions and caveats in the SQUG GIP. All equipment damages or failures received reviews for root causes and to determine if any caveat changes/additions were needed.

SPECIFIC COMMENTS

1. *On page 1, acronyms (i.e. FOAKE, USGS, CDMG) should be spelled out before they are used.*
2. *On page 6, the database should include "description of anomalies, damage and failure," location of equipment (including the building) relative to the location where the ground motion was measured or estimated and "estimated g level."*
3. *On page 10, "education background" should be included in the requirements of the qualified personnel.*

SQUG has incorporated these comments. Education background will be that required for Seismic Capability Engineers in the SQUG GIP.

REQUESTED INFORMATION

The following is the staff's request for additional information (RAI):

1. *Explain why you state, in the first paragraph on page 1 of the Procedure, "The experience data from sites subjected to strong ground motion earthquakes up to the 1985 time frame have been reviewed by the Senior Seismic Review and Advisory Panel (SSRAP) and approved as a part of the USI A-46 program efforts by the USNRC," when only a part of your data base was reviewed by SSRAP, and some of the data submitted as part of the USI A-46 program to NRC was rejected on overestimation of the ground motion. In addition, many of the ground motion estimates in the earthquake experience data in the Topical Report "BWROG Report for Increasing MSIV Leakage Rate Limits and Elimination of Leakage Control Systems" submitted by the BWR Owners' Group are similar to the data provided in Table 1 of your current submittal and this data is being questioned by the NRC. (NRC letter from E. H. Trottier to T. A. Green of GE Nuclear Energy, dated March 29, 1995.) In Section II.5 of its Supplemental Safety Evaluation*

Report No. 2 (SSER No. 2) dated May 22, 1992, the staff indicated that it had not reviewed one of the SQUG's database summary reports. Identify and provide the specific quotes from SSRAP and NRC documents which you asserted to support your statement.

It was SQUG's understanding that SSRAP and the NRC Staff had reviewed the database information contained in the February 1987 draft of GIP-2 Reference 4 and accepted it as valid earthquake data. That information is a subset of the information contained in the database. It was not meant to imply that the NRC had reviewed and approved the entire database. The statement has been deleted from the procedure.

2. *Explain the apparent discrepancy where on Page 2 in Section 3.0, you state that in Table 1, 87 of the 124 sites in the database are post-1985 sites, while in Table 1 you indicate that only 16 of the sites listed have ground motion that were measured by an instrument at the site. Also, it is not clear how far these instruments were from the facility. These statements can mislead the reader to think that all 87 sites have accurate ground motions. Clarify and justify your statement so that it is evident to the reader how much dependable ground motion information is available.*

The intent of this paragraph was simply to indicate that about one third of the data in the electronic database were from "pre-1985" earthquakes and two-thirds were from "post-1985" earthquakes. It does not imply that all of the post-1985 earthquake sites had ground motions that were measured by an instrument at the site. This paragraph has been deleted.

The issue of dependable ground motion is addressed in the response to Item 5.

3. *On page 2, in Section 3.0, the seismic experience database was briefly described. However, the definition and scope of the experience database were not clearly described. An acceptable experience database should contain a well-organized and controllable document that can be referenced and tracked. Thus the earthquake experience database should start from the raw data that is collected following an earthquake database site investigation. Then, the data should be screened, studied, and validated for the acceleration spectrum that was claimed for the equipment capacity. In order for the staff to evaluate the adequacy of the procedure for gathering and validating the earthquake experience data, the details of the database have to be reviewed and evaluated by the staff. Therefore, (1) define clearly the scope of the so-called "Earthquake Experience Data Base," (2) describe the details of the equipment items in a referable and controllable report or electronic database, and (3) submit the report or electronic database for the staff's review. (The database may be divided into two or three groups to include those data from pre-1985, post-1985, and future collections).*

The requested information was previously submitted under separate cover (Reference 5) for the staff's review.

4. *It is stated in Section 3.0 (page 3) that the peak acceleration of the ground motion of a data base site could be as low as 0.10g to 0.15g. It is further stated that a "much larger and diverse set of equipment has been subjected to the lower level motion than the higher level motion." The merit of all experience data including those from the low-level ground motion is acknowledged. However, this merit can be realized only if data are*

properly applied. One application is for direct comparison with site-specific equipment items. On the other hand, the equipment capacity estimation could be erroneous and unconservative if the low-and high-level data are combined such that data could be used to define the diversity of equipment and the high level ground motion data are used to define the capacity of equipment. Specify the use of such low-motion data and, if they are combined with the high-level ground motion data to develop generic capacity levels, justify why they could not produce unconservative results.

As was stated in the last paragraph in this section, if data from lower motion sites were to be used to expand a generic equipment class definition, the generic capacity spectrum associated with that class would have to be reduced so as not to produce unconservative results. However, this particular paragraph has to do with use of the data, which is outside the scope of the procedure. It has been removed from the procedure.

5. *On the top of page 3 you make the statement that "Measured or estimated ground accelerations for data base sites range from approximately 0.010g to 0.70g." Also, Table 1 of the report contains a list of about 125 earthquake-facility pairs with estimates of the average of the two horizontal components of peak ground acceleration (PGA) at the facility for 115 pairs. Of these 115 earthquake-facility pairs, the table indicates that for 20 of the facilities the PGA estimated is based on the nearest accelerographs with no statement as to the distance between the facility and accelerographs. Furthermore, Section 4.2 (Ground Motion Estimates) of the reports states that "Sites with no available instruments within a reasonable distance require estimation of average peak acceleration (a site response spectrum is unavailable for those sites). These ground motion estimates are made based upon review of motion estimates by recognized agencies (e.g. USGS, CDMG, etc.)."*

   The ground motion from an earthquake at a particular site is a function of the earthquake source characteristics such as the magnitude, focal mechanism, radiation pattern, stress drop, location of asperities and fault rupture propagation history, and depth and orientation of the fault. It is also a function of the distance of the facility to the fault and the propagation properties of the rocks between them. The geology immediately under the facility site can also have an especially large effect on the amplitude and frequency content of the ground motion at the facility. It has been observed from numerous earthquakes that the variation of the ground motion values within short distances can be substantial. Therefore, it is inappropriate to assign ground motion recorded at one location to a facility at another location without a very thorough analysis. The appropriate distance for a free field strong motion recording instrument used to characterize the earthquake ground motion experienced by the structure is on the order of one to two structure diameters from the structure. Even at this distance the foundation material of the structure and the recording instrument should be essentially the same.

   In view of this, to enable the NRC staff to perform its review of the Procedure, for each of the earthquake-facility pairs in the experience data base provide the following information:

a) *The name, location (latitude and longitude or street address or nearest highway intersection), and foundation geology (i.e., rock, deep soil, shallow soil) of the facility for which the ground motion estimate was made.*

b) *The name, date, time and epicenter, magnitude of the earthquake and distance of the facility to the closest part of the earthquake fault rupture.*

c) *The 5 percent of critical damping response spectra of the ground motion estimated for each horizontal component at the facility from the earthquake.*

d) *The method used to estimate the ground motion at the facility. If the ground motion is based on actual ground motion recordings, provide the location (latitude and longitude or street address or nearest highway intersection) and foundation geology of the recording station and its distance from the facility and its distance to the closest part of the fault rupture. If the estimation is based on a method other than an actual recording of the earthquake ground motion or if the recording station is not collocated with the facility (distance from structure to instrument greater than 200 meters), describe the method used to estimate the ground motion in detail and provide any ground motion attentuation equations which may have been used to obtain the estimate. For ground motion estimates based "....upon review of motion estimates by recognized agencies (e.g. USGS, CDMG, etc.)," provide copies of the material upon which your estimate is based.*

This information is beyond what was collected in Reference 3, which established the precedent which SQUG followed in developing the initial database. SQUG has developed a procedure for providing this information. It is in Section 4.2 of the revised procedure, along with three examples in the appendix. After NRC staff review of this procedure, the required information will be developed for additional earthquake-facility pairs and incorporated into the electronic database. The peak ground acceleration estimates in Table 1 of the revised procedure have been deleted.

6. *On page 3, of the Procedure you state that "the data obtained at the lower level of ground motion sites was used as confirmatory data in support of the conclusions which could be reached based on equipment performance at the highest level sites." It is not clear what this statement means. Provide a detailed description of the analysis that was performed and the justification for the quoted statement.*

This sentence was intended to explain that SSRAP based its conclusions on all of the data it reviewed, not just from the four sites on which it based the capacity spectrum. While SSRAP based the capacity spectrum on the four higher level ground motion sites, the data from all of the sites were to determine the equipment class inclusion rules and caveats. We have revised the procedure to clarify the statement.

7. *Section 4.1 states that "any damage or failures that would result in changes to any of the SQUG methodology are incorporated into a revision of the GIP..." Are there any examples of equipment failures, significant or insignificant, in the post 1985 experience data, leading to the potential GIP changes? If so , provide detailed examples including data on equipment damage/failures so that the effectiveness of the procedure can be evaluated.*

So far, there have been no changes to the GIP. There were several reports of damage from the Guam and Northridge earthquakes. These reports of damage were followed up by SQUG. The investigations were described in articles in the SQUG Newsletter in 1994 (Reference 6) and 1995 (Reference 7), which were distributed to SQUG member utilities,

SSRAP members, certain NRC staff and others. The investigations concluded that GIP changes were not needed.

8. *As implied in Section 4.2, the ground motion estimates are made from "instruments available on-site, instruments available within several Km," or "no recordings at all." the practical difficulties, e.g., unavailability of recording instruments, information concerning soil conditions, etc., are recognized. But, a question still remains regarding the reliability of such ground motion estimates and was reviewed by a group of independent experts (e.g., the SSRAP), and expert judgments played a major role in this usage. It appears from the procedures described in the document that similar expert review and judgments are not a requirement any longer. Justify the reliability of the ground motion estimates, given the uncertainties, without a commitment to receive expert assistance.*

   Furthermore, on page 7 in Section 4.6.1 of the Procedure you state "New earthquake experience data receives a peer review by the SQUG Steering Group members and by selected industry experts who are consultants to the Steering Group." Are any of the members of the Steering Group or the consultants seismologists knowledgeable in strong ground motion estimation? If yes, provide their names. By using SQUG Steering Group members as the peer reviewers, you lose the independent nature of the peer review. The peer review group should conduct independent reviews.

SQUG has revised the procedure to commit to having a qualified seismologist perform an independent review of ground motion estimates developed for future additions to database. The requirement is in Section 4.6.2.

9. *A threshold spectral acceleration or reduction factor of 0.75 was presented in the last paragraph of Section 4.2. Provide the technical bases for the number (i.e., 0.75).*

Section 4.2 has been substantially changed to respond to Item 5. This particular statement had to do with use of the data, which is outside the scope of the procedure. Statements having to do with use of the data have been eliminated from the procedure.

10. *On page 9 in Section 5.0 you state, "Data base sites which have several ground motion recordings beyond 3 km proximity can use a carefully applied triangulation averaging approach as described in Section 4." However, Section 4 does not describe that approach, it just has the same statement as Section 5.0 (that a triangulation approach can be used). Provide a detailed description of your triangulation approach with actual case histories including the input data used and the ground motion estimate obtained. Explain how this approach considers such factors as focal mechanism radiation pattern, differences in site geology, different distances to the fault, etc., which can lead to large uncertainty in strong ground motion estimates as noted in Question 5 above.*

Section 4.2 of the revised procedure describes how SQUG proposes to estimate the ground motion at a site under various conditions.

11. *If information from new earthquakes indicates that equipment previously assumed to be able to survive a certain ground motion level has been damaged at a lower ground motion level, will the equipment be removed from the GIP and will the utilities and the NRC be notified pursuant to Part 21 of Title 10 of the Code of Federal Regulations?*

SQUG has separately committed to investigating reports of earthquake damage which could potentially require a change to the GIP, in the definition of an equipment class, addition of a caveat or modification of the Bounding Spectrum. Should the investigation of such a damage report show that such a change is needed, SQUG will follow its procedure for revising the GIP, which has been approved by NRC. This procedure requires notification of SQUG members of any data which require changes to the GIP. It is the responsibility of each licensee to determine if the information provided by SQUG is reportable under the regulations.

Enclosure 2 to
SQUG Letter Dated
February 17, 2000

PROCEDURE FOR GATHERING AND VALIDATING EARTHQUAKE EXPERIENCE DATA

REVSION 1

1.0 PURPOSE

The purpose of this procedure is to document the process that has been used by the Seismic Qualification Utility Group (SQUG) for collection, evaluation and validation of earthquake experience data which are contained in the SQUG Electronic Earthquake Experience Database (Reference 1).

This procedure also documents the process to be used in the future by SQUG to collect, evaluate and validate earthquake experience data as requested in Reference 2.

The continual advancement in the understanding of seismic behavior of structures, systems, and components is essential for safe and reliable engineering. Consequently, a controlled process that allows for the systematic collection of seismic experience data is an expected and essential element.

2.0 BACKGROUND

Earthquake experience data form the underlying backbone for much of the methodology SQUG developed to resolve the USI A-46 issue (Reference 3). The collection of earthquake experience data has been a collaborative effort between EQE International, SQUG and the Electric Power Research Institute (EPRI). An initial data collection effort in 1981-1982 was documented in Reference 4. This was reviewed by NRC, and the level of information provided was found sufficient for the earthquake experience-based approach in NUREG-1030 (Reference 5). Further data were collected in 1982-1985 for use by the Senior Seismic Review and Advisory Panel (SSRAP). These data, and the procedure used to collect them, were documented in the Twenty Classes Report (Reference 6). The SSRAP review of these data was documented in the SSRAP Report (Reference 7). NRC review of the SSRAP Report was documented in Reference 2.

Collection of earthquake experience data continued after 1985. The procedure for collecting and documenting the data was the same as that reported in References 4 and 6. In 1993, an electronic database of the earthquake data was developed. The current version of this database is described in Reference 1. Copies of this report, and the electronic database itself, were submitted for NRC review in May, 1998 (Reference 8).

3.0 SEISMIC EXPERIENCE ELECTRONIC DATABASE

The seismic experience electronic database contains data on equipment from 124 facilities (sites) located in the strong-motion areas of 24 earthquakes that have occurred

in California, Latin America, and the western Pacific since 1971. The earthquakes and facilities included in the electronic database are summarized in Table 1.

A quick inspection of Table 1 reflects the fact that 15 of the 24 earthquakes within the electronic database are "post 1985" earthquakes. In addition, 87 out of the 124 database sites are post-1985 sites. Thus, the post-1985 data within the electronic database, collected subsequent to Reference 6, is estimated to be approximately 2/3 of the total data.

The data was compiled through surveys of the following types of facilities:

- Fossil-fueled power plants
- Hydroelectric power plants
- Electrical distribution substations
- Oil processing and refining facilities
- Water treatment and pumping stations
- Natural gas processing and pumping stations
- Manufacturing facilities
- Large commercial facilities

In general, data collection efforts focused on facilities located in the areas of strongest ground motion for each earthquake investigated. Facilities were sought that contained substantial inventories of mechanical or electrical equipment, or control and instrumentation systems. Because of the number of earthquake-affected areas and types of facilities investigated, there is a wide diversity in the types of installations included in the database. For the types of equipment similar to those installed in A-46 plants, this includes a wide diversity in age, size, configuration, application, operating conditions, manufacturer, type of building, location within building, local soil conditions, quality of maintenance, and quality of construction.

The database includes a total of 24 earthquakes ranging in Richter magnitude from 5.7 to 8.1. Measured or estimated ground accelerations for database sites range from approximately 0.10g to 0.70g. Local soil conditions range from deep alluvium to rock. The buildings housing the equipment of interest have a wide range in size, and type of construction. As a result, the database covers a wide diversity of seismic input to equipment, in terms of seismic motion amplitude, duration, and frequency content.

SSRAP concluded that the data from the pre-1985 facilities, listed in Table 1, demonstrated the seismic ruggedness of equipment within these facilities up to the motion bounds represented by the average response spectrum of the four highest ground motion level sites (the SQUG Reference Spectrum). While the data from the four highest motion sites were used to establish the capacity bound for the functional performance of equipment (excluding relay chatter), the data obtained at the lower level ground motion sites were used as confirmatory data in support of the conclusions which could be reached based on equipment performance at the highest level sites. Many of the caveats and attributes applied to the definition of the equipment classes, for which the Reference Spectrum was applicable, utilized the observed performance of equipment at these lower motion level sites. Thus, the entire database was utilized to

demonstrate that, within the caveat restrictions, no item of equipment had failed, up to the level represented by the Reference Spectrum.

4.0 COLLECTION AND VALIDATION OF EARTHQUAKE EXPERIENCE DATA

The process used to collect and validate the post-1985 set of data, which has been added to the electronic database is shown in Figure 1 and described within this section. It is important to note that process used to collect the post-1985 data has been enhanced from the earlier methods to collect the original pre-1985 data. The post-1985 data collection methods had the benefit of the "lessons learned" from previous (1971-1985) earthquake investigation, in addition to the fact that all the engineers gathering the data for the most recent earthquakes had the benefit of the formal SQUG training. The main elements of the data collection process are:

- Type of data collected (4.1)
- Ground motion estimates (4.2)
- Treatment of damage, failures and anomalies (4.3)
- Screening and Documentation (4.4)
- Qualification of Personnel (4.5)
- Peer Review (4.6)

4.1 Type of Data Collected

It is desirable to conduct the site investigation in two phases. The first phase is an immediate reconnaissance after the earthquake to obtain perishable data and to establish contact with the facility operators. The second phase, if warranted, is a more detailed site visit conducted a few months after the earthquake when the facility has returned to normal operation, to see if any earthquake related operational issues have occurred and to obtain more detailed equipment data as necessary.

Information on each database facility, its performance during the earthquake, and any damage or adverse effects caused by the earthquake were collected through the following sources:

- Interviews with the facility management and operating personnel usually provide the most reliable and detailed information on earthquake effects. At most facilities several individuals are consulted to confirm or enhance details. In many cases, interviews are recorded on audiotape.

- Facility operating logs are a written record of the conditions of the operating systems before and after the earthquake. Operating logs list problems in system operation associated with the earthquake and usually tabulate earthquake damage to the facility. Operating logs are also useful in determining the amount of time the facility may have been out of operation following the earthquake and any problems encountered in restarting the facility. These logs are reviewed as part of the data collection process. Copies (if allowed by the facility operator) are obtained as part of the data records and for future reference.

- The facility management typically produces a report summarizing the effects of the earthquake following detailed inspections. These reports normally describe causes of any system malfunctions or damage, and typically include any incipient or long-term effects of the earthquake.

- Immediate facility survey - If the facility can be surveyed immediately following the earthquake, as has been the case in 17 of the 24 earthquakes included in the database, earthquake damage can often be inspected prior to repairs.

- Walkdown inspection notes, sketches, anchorage details, photographs, catalog cuts, etc. are all attempted to be collected at the site. The cooperation of the facility operators is necessary for this collection effort. Only in rare instances, have facilities placed restrictions on data (e.g. no photographs) that can be obtained from a given site.

Standard procedures used in surveying database facilities focus on collecting all information on damage or adverse effects of any kind caused by the earthquake. In addition, data on equipment that performed satisfactorily, i.e., "success" data, is collected. Except for sites that experienced very high seismic motion (in excess of 0.50 g peak ground acceleration), seismic damage to well-engineered facilities is normally limited to only a few items. All anomalies, damage and/or failures are documented within both the database and within the appropriate earthquake reconnaissance report. Any damage or failures that would result in changes to any of the SQUG methodology are incorporated into a revision to the GIP and transmitted to NRC per procedure and to all SQUG members.

4.2 Ground Motion Estimates

The procedure used to estimate a ground-motion response spectrum at an individual SQUG database site will depend on the number and location of strong-motion recordings that are available from the earthquake that affected the site. The procedure for doing this is summarized below.

4.2.1 Ground-Motion Estimation Procedure

There are four possible scenarios for estimating a ground-motion response spectrum at a database site depending on the availability of strong-motion recordings as follows:

1. There is a recording at the database site,

2. There are one or more recordings within close proximity of the database site,

3. There are multiple recordings from the earthquake, but none are within close proximity of the database site,

4. There are none or only a few recordings from the earthquake and none are within close proximity of the database site.

The specific procedure for estimating a response spectrum at the database site for each of these scenarios is given below. In each procedure, the term "appropriate attenuation relationship" refers to a spectral attenuation relationship which was derived either empirically or theoretically for a region having a similar tectonic environment, similar earthquake source characteristics, and similar wave-propagation (attenuation) characteristics as the region in which the database site is located; which is applied using earthquake-specific estimates of magnitude, closest distance to the fault rupture, and style of faulting; and which represents local site conditions that are similar to those at the database site . The term "similar site conditions" refers to local soil conditions that fall into the same site classification as defined in Section 4.2.2.

Scenario 1. In this scenario there is a recording at the database site. In order for a recording to meet this criterion, it cannot be located any further than about two building dimensions (in plan view) from the database site. This recording will be used without modification to represent the response spectrum at the database site if the recording site and database site have similar site conditions. If the two sites do not have similar site conditions, the recorded response spectrum will be adjusted using the procedure described in Section 4.2.2.

Scenario 2. In this scenario there are one or more recordings within close proximity of the database site, but none are within about two building dimensions. Whether a recording is within close proximity to the database site will depend on the distance of the recording and database sites from the earthquake rupture. In general, the distance of the recordings from the database site should not exceed about 5 km unless sufficient justification is given. If the distance between any recording site and the database site is a significant fraction of the distance from these two sites to the earthquake rupture (e.g., greater than about 10%), the recorded response spectrum will be adjusted using scaling factors derived from a set of appropriate attenuation relationships. If the recording site and database site do not have similar site conditions, the recorded response spectrum will be adjusted using the procedure described in Section 4.2.2. The response spectrum at the database site will be estimated as the average of the recorded or adjusted response spectra.

Scenario 3. In this scenario there are multiple recordings from the earthquake, but none are within close proximity of the database site. In this case, the recordings are far enough away from the database site that their response spectra will need to be adjusted. This will be done by using spectral scaling factors derived from a set of appropriate attenuation relationships that have been adjusted to have the same average amplitude as the recorded response spectra. To avoid variability due to source radiation pattern and source directivity, a recording will be used only if it has an azimuth (direction with respect to the earthquake hypocenter) that is within about ±22.5 degrees of the azimuth of the database site. If less than about 5 recordings meet these criteria, Scenario 4 will be used to estimate the ground motion at the database site. If the recording site and database site do not have similar site conditions, the recorded response spectrum will be adjusted using the procedure described in Section 4.2.2. The response spectrum at the database site will be estimated as the average of the adjusted response spectra.

Scenario 4. In this scenario, there are none or only a few recordings from the earthquake and none are within close proximity of the database site. In this case, a set of appropriate attenuation relationships will be used to estimate the response spectrum

at the database site based on a seismological model of the earthquake. The seismological model will include an estimate of the earthquake's magnitude, seismic moment, stress drop, rupture characteristics, focal depth, and fault-rupture geometry (i.e., length, width, and dip of the earthquake rupture plane). If an appropriate set of attenuation relationships is not available, a stochastic simulation model will be used to adjust a set of attenuation relationships from another (host) region, if there is sufficient seismological data available to model the source and wave-propagation characteristics of the host and target (database site) regions. Application of the stochastic simulation model will include, in addition to those seismological parameters specified above, an estimate of the shear-wave velocity and attenuation (Q) of the hypocentral region of the earthquake and of the earth's crust between the earthquake and the database site. The response spectrum at the database site will be estimated as the mean of the response spectra derived from the adjusted attenuation relationships.

4.2.2 Local Site Conditions

In order for a strong-motion recording to be used in the estimation of the response spectrum at a database site, it must either: (1) be located on similar site conditions, or (2) be modified to account for the differences in these site conditions. Whether a recording site and a database site have similar site conditions will be based on a comparison of the available geological and geotechnical data that are available for the sites.

A recording and database site will be considered to have similar site conditions if they have the same Soil Profile Type as defined in the 1997 edition of the *Uniform Building Code (UBC)* or the 1997 edition of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, and the total depth of sediments beneath the site are sufficiently similar (i.e., within about 10% of each other). In such a case, no adjustment of the recorded response spectrum will be required. The Soil Profile Type, designated S_A through S_F as defined in the *UBC* and *NEHRP Recommended Provisions*, will be defined in terms of one or more of the following: (1) average shear-wave velocity, (2) average standard penetration resistance (SPT N-value), (3) average standard penetration resistance of cohesionless soil layers, and (4) average undrained shear strength of cohesive layers. In all cases, the average is taken over the top 30 meters (100 feet) of the soil profile.

Ideally, there should be sufficient geotechnical data at both the recording and database sites with which to unambiguously determine the Soil Profile Type. It is more likely, however, that there will be only general near-surface geological data at the two sites. The exception will be those recording sites for which special studies have been conducted to determine the lithology and/or shear-wave velocity profile at the site and those database sites for which a geotechnical report is available. If sufficient geotechnical data are not available, general geologic descriptions from large-scale geologic maps will be used to define the Soil Profile Type using available empirical correlations between shear-wave velocity and geological information. The only time that this procedure will not be used is when a site is located in an area of complex geology where its classification in terms of a given Soil Profile Type is ambiguous. If such is the case for a recording site, the site's response spectrum will be excluded from consideration. If such is the case for the database site, the database site will be

excluded from consideration until sufficiently accurate geotechnical and/or geological data can be obtained.

When an adjustment to the recorded response spectrum is required because its Soil Profile Type is different than that of the database site, this adjustment will be based on one or more of the following as appropriate: (1) empirical site factors derived from a set of appropriate spectral attenuation relationships, (2) site factors recommended in the *UBC* and *NEHRP Recommended Provisions*, and (3) other site factors derived from special empirical, theoretical, or laboratory studies. When an adjustment to the recorded response spectrum is required because its sediment depth is different than that of the database site, this adjustment will be based on empirical correlations between spectral acceleration and sediment depth.

Three example ground motion estimates are provided in Appendix A.

4.3 Treatment of Damage, Failures and Anomalies

As noted in Section 4.1, any equipment anomalies, damage, or failures receive a focused investigation during the data collection effort. A "root cause" evaluation is prepared which either (1) concludes that existing SQUG caveats would prevent the noted equipment damage, or failure anomaly, or (2) recommends additional SQUG caveats applicable for the equipment class with the observed equipment anomaly, damage, or failure to ensure that the observed effect is addressed in SQUG walkdown procedures. If warranted, the GIP will be revised after appropriate review by peer review groups as presented in Reference 9 and approved for use by the NRC in Reference 10.

.4.4 Experience Data Screening and Documentation

The raw data that is collected following an earthquake database site investigation is organized and screened prior to entry into the electronic database. The data is reviewed to ensure that enough information exists on each equipment component to meet minimum standards for database inclusion. Components with unexplained anomalies, damage or failures are placed on a list for further investigation. By the time a new piece of equipment is entered into the database it has:

- Photographs
- Written description of the component
- Make, model number and operating status
- Location in structure
- Anchorage and load path description
- Pertinent sketches, catalog cuts, drawings
- Resolution on any problems experienced in the seismic event

4.5 Personnel Qualified to Collect the Data

SQUG has maintained high standards relative to the background and experience of the engineers and earth-science professionals who collect and interpret the data which is to be entered into the database.

4.5.1 Equipment Data

The engineers who will collect and interpret equipment data are required to have the following minimum experience:

- Five years of experience in the fields of seismic testing, analysis, structural dynamics and earthquake effects.
- SQUG training
- Experience with equipment (mechanical and electrical) design and operations
- Working knowledge of SQUG GIP and all SQUG reference documents

The data collection engineers are expected to have a thorough background in the potential earthquake effects on the wide variety of equipment which are included within the SQUG evaluation procedure (e.g. tanks, cable trays, pumps, valves, MCC, batteries, etc.). The project leader for a SQUG research team investigating any particular earthquake will have the additional requirement of having participated in the past investigation of at least five different earthquake database sites.

4.5.2 Ground Motion Data

The earth-science professionals who will collect and interpret strong motion data are required to have the following minimum experience:

- Ten years of experience in the fields of earthquake seismology, engineering seismology, earthquake geology, strong-motion seismology, and/or geotechnical earthquake engineering.
- Experience in analyzing and interpreting strong-motion recordings and response spectra.
- Experience with developing and/or using strong-motion attenuation relationships.
- Experience with developing seismological models for defining earthquake rupture characteristics.
- An understanding of the impact of local soil conditions on strong-motion amplification.

4.6 Peer Review

To assist in developing the A-46 program methodology, SQUG and the USNRC jointly selected and supported a five-member Senior Seismic Review and Advisory Panel (SSRAP) in June 1983 to make an independent assessment of whether certain classes of equipment in operating nuclear power plants in the United States have demonstrated sufficient ruggedness in past earthquakes so as to render an explicit seismic qualification unnecessary. SSRAP operated as an independent peer review body with all of its finding submitted concurrently to both SQUG and the USNRC. During their period of involvement, SSRAP issued several positions on issues presented by both the USNRC and SQUG and issued two final reports. The SSRAP Report is considered to constitute the peer review of the data from earthquakes which occurred through 1985. For earthquakes which occurred after 1985, the following peer review applies.

4.6.1 Equipment Data Review

New earthquake experience data receive a peer review by the SQUG Steering Group members and by selected industry experts who are consultants to the Steering Group. These peer reviewers conduct a detailed review of all instances of damage and failure of equipment types pertinent to the SQUG methodology. The Steering Group ensures that reasonable conclusions have been made relative to the cause and effect of any anomalies. The Steering Group is also responsible for ensuring that the SQUG procedures are updated to reflect any "lessons learned" coming out of the earthquake review effort. This would typically entail modification of caveats within the GIP. The Steering Group does a general review of the "success" data which will be added to the experience database following a new earthquake. This is intended to ensure reasonableness of this new data.

4.6.2 Ground Motion Review

The ground motion estimates prepared per Section 4.2 are independently reviewed by an earth-science professional knowledgeable in ground motion estimation. This person should have the same minimum experience required by the earth-science professional who develops the ground motion estimates as specified in Section 4.5.2.

5.0 REFERENCES

1. EPRI Report TR-110781, "SQUG Electronic Earthquake Experience Database User's Guide, WINSQUG Version 2.0," Revision 0, May 1998.

2. Generic Letter 87-02, Supplement No. 1, transmitting Supplemental Safety Evaluation Report No. 2 (SSER No. 2) on SQUG Generic Implementation Procedure, Revision 2, as corrected on February 14, 1992 (GIP-2), U.S. Nuclear Regulatory Commission, Washington, D.C., May 22, 1992.

3. SQUG Generic Implementation Procedure, Revision 2, issued December 2, 1988.

4. Yanev and Swan, "Program for the Development of an Alternative Approach to Seismic Equipment Qualification," Vols. 1 and 2, September 1982.

5. NUREG-1030, "Seismic Qualification of Equipment in Operating Nuclear Power Plants," February 1987.

6. EPRI Report NP-7149, "Summary of the Seismic Adequacy of Twenty Classes of Equipment Required for the Safe Shutdown of Nuclear Plants," Electric Power Research Institute, Palo Alto, CA, prepared by EQE Engineering Consultants, March 1991.

7. SSRAP, "Use of Seismic Experience and Test Data to Show Seismic Ruggedness of Equipment in Nuclear Power Plants," Revision 4.0, February 28, 1991.

8. EPRI (R. Kassawara) letter to NRC (P. Chen), dated May 19, 1998, "TR-110781, Rev. 0, 'SQUG Electronic Earthquake Experience Database User's Guide,' May, 1998, and the Electronic Database WINSQUG V2.0 (set of two CD-ROMs)."

9. SQUG (N. Smith) letter to NRC (J. Stolz), dated May 16, 1997, "Generic Implementation Procedure (GIP) for Seismic Verification of Nuclear Power Plant Equipment, Revision 3, Updated 05/16/97, and Procedure for Revising the GIP, Revision 3."

10. NRC (J. Stolz) letter to SQUG (N. Smith) dated December 4, 1997, "Supplemental Safety Evaluation Report No. 3 (SSER No. 3) on the Review of

Revision 3 to the Generic Implementation Procedure for Seismic Verification of Nuclear Power Plant Equipment, Updated May 16, 1997, (GIP-3).

Table 1

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
San Fernando, CA Earthquake 1971 (M6.5)	Sylmar Converter Station	Large electrical substation
	Rinaldi Receiving Station	Large electrical substation
	Valley Steam Plant	Four-unit gas-fired power plant
	Burbank Power Plant	Six-unit gas-fired power plant
	Glendale Power Plant	Five-unit gas-fired power plant
	Pasadena Power Plant	Five-unit gas-fired power plant
Point Mugu, CA Earthquake 1973 (M5.7)	Ormond Beach Power Plant	Large two-unit oil-fired power plant
Ferndale, CA Earthquake 1975 (M5.5)	Humboldt Bay Power Plant	Two gas-fired units, one nuclear unit
Imperial Valley, CA Earthquake 1979 (M6.6)	El Centro Steam Plant	Four-unit gas-fired power plant
	Drop IV Hydro. Plant	Two-unit hydroelectric plant
Humboldt, CA Earthquake 1980 (M7.0)	Humboldt Bay Power Plant	Two gas-fired units one nuclear unit

Table 1 (Continued)

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
Coalinga, CA Earthquake 1983 (M6.7)	Getty Oil Pumping Plant	Pumping station feeding oil pipeline from Coalinga area
	Union Oil Butane Plant	Petrochemical facility to extract butane and propane from well waste gas
	Shell Water Treatment Plant	Petrochemical facility to demineralize water prior to steam injection into oil wells
	Coalinga Water Treatment Plant	Water purification facility
	Shell Tank Farm No. 29	Tank farm
	Pleasant Valley Pumping Plant	Pumping station from the San Luis Canal to the Coalinga Canal
	San Luis Canal Pumping Stations	Agricultural pumping stations taking water from the San Luis Canal
	Gates Substation	500 kV electrical substation
	Kettleman Compressor Station	Natural gas pipeline booster station
Morgan Hill, CA Earthquake 1984 (M6.2)	IBM/Santa Teresa Facility	Large computer facility for software development
	San Martin Winery	Wine fermentation facility and tank farm
	Metcalf Substation	500 kV electrical substation

Table 1 (Continued)

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
	Mirassou Winery	Wine fermentation facility and tank farm
Chile Earthquake 1985 (M7.8)	Bata Shoe Factory	Tannery and shoe manufacturing facility
	Llolleo Water Pumping Plant	Water pumping and filtration plant
	Rapel Hydroelectric Plant	Five-unit hydroelectric plant
	Concon Petroleum Refinery	Petrochemical facility producing fuel oil, asphalt, gasoline, and other petroleum products
	Oxiquim Chemical Plant	Chemical facility producing various products, including feed stock for paint ingredients
	Concon Water Pumping Station	Water pumping station
	Renca Power Plant	Two-unit coal-fired power plant
	Laguna Verde Power Plant	Two-unit coal-fired peaking plant
	Las Ventanas Copper Refinery	Copper refinery/foundry/power plant
	Las Ventanas Power Plant	Two-unit gas-fired power plant

Table 1 (Continued)

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
Mexico Earthquake 1985 (M8.1)	Infiernillo Dam	Six-unit hydroelectric plant
	La Villita Power Plant	Four-unit hydroelectric plant
	SICARTSA Steel Mill	Large steel mill
	Fertimex Plant	Large fertilizer production plant
Adak, Alaska Earthquake 1986 (M7.5)	Adak Naval Base	Diesel-electric power plants, electrical substations, water treatment plant, steam plants
North Palm Springs, CA Earthquake 1986 (M6.0)	Devers Substation	500 kV electrical substation
	Whitewater Hydro. Plant	Small hydroelectric power plant
Chalfant Valley, CA Earthquake 1986 (M6.0)	Hi-Head Hydro Plant	Small one-unit hydroelectric plant
San Salvador Earthquake 1986 (M5.4)	Soyapango Substation	115 kV substation
	San Antonio Substation	115 kV substation
Bay of Plenty, New Zealand Earthquake 1987 (M6.25)	Edgecumbe Substation	230 kV substation
	New Zealand Distillery	Liquor distillery
	Caxton Paper Mill	Paper and pulp mill

Table 1 (Continued)

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
Bay of Plenty, New Zealand Earthquake 1987 (M6.25) (Cont.)	Kawerau Substation	230 kV substation
	Whakatane Board Mill	Paper mill producing cardboard
	Matahina Dam	Two-unit hydroelectric plant
Whittier, CA Earthquake 1987 (M5.9)	Olinda Substation	230 kV substation
	SCE Central Dispatch Headquarters	Data Processing Center
	SCE Headquarters	Large office complex and data processing center
	California Federal Bank Facility	Data processing facility
	Ticor Facility	Data processing facility
	Mesa Substation	230 kV substation
	Sanwa Bank Facility	Data processing facility
	Alhambra Station	Telephone switching station
	Rosemead Station	Telephone switching station
	Central Station	Telephone switching station
	Wells Fargo Bank Facility	Data processing facility

Table 1 (Continued)

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
Whittier, CA Earthquake 1987 (M5.9) (Cont.)	Center Substation	230 kV Substation
	Lighthype Substation	230 kV Substation
	Del Amo Substation	230 kV Substation
	Commerce Refuse-to-Energy Plant	Trash-burning power plant
	Pasadena Power Plant	Five-unit gas-fired power plant
	Glendale Power Plant	Five-unit gas-fired power plant
	Puente Hills Landfill Gas & Energy Recovery Plant	Methane burning power plant
Superstition Hills (El Centro), CA 1987 (M6.3)	Mesquite Lake Resource Recovery Plant	Organic waste burning power plant
	El Centro Steam Plant	Four-unit gas-fired power plant
Loma Prieta Earthquake 1989 (M7.1)	Moss Landing Power Plant	Seven-unit gas-fired power plant
	Gilroy Energy Cogen Plant	Combined gas turbine and steam plant
	Cardinal Cogen Plant	Combined gas turbine and steam plant
	University of California at Santa Cruz	Diesel cogeneration plant and HVAC plants

Table 1 (Continued)

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
Loma Prieta Earthquake 1989 (M7.1) (Cont.)	Hunter's Point Plant	Three-unit gas-fired power plant
	Portrero Plant	Two-unit gas-fired plant
	Metcalf Substation	500 kV substation
	San Mateo Substation	230 kV substation
	National Refractory	Large brick & magnesia extraction plant
	Green Giant Foods	Food processing and cold storage plant
	Watsonville Wastewater Treatment	Sewage treatment plant
	Santa Cruz Station	Telephone switching station
	Watsonville Station	Telephone switching station
	Seagate Technology Watsonville	Electronic manufacturing facility
	Santa Cruz Water Treatment	Water purification facility
	Soquel Water District	Pumping stations & storage tanks
	Lipton Foods	Food processing and packaging facility

Table 1 (Continued)

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
Loma Prieta Earthquake 1989 (M7.1) (Cont.)	Lone Star Cement	Cement factory
	Watkins-Johnson Instruments	Electronic manufacturing plant
	Rinconada Water Treatment Plant	Water purification facility
	IBM/Santa Teresa Facility	Software development laboratory
	EPRI Headquarters	Office and data processing complex
Central Luzon, Philippines Earthquake 1990 (M7.7)	Baguio Station	Telephone switching station
	Cabanatuan Substation	230 kV substation
	La Trinidad Substation	230 kV substation
	San Manuel Substation	230 kV substation
	Moog Manufacturing Plant	Electronic manufacturing plant
Valle de Estrella, Costa Rica Earthquake 1991 (M7.4)	Bomba Water Treatment Plant	Water Treatment Plant
	Cachi Dam	Large hydroelectric plant
	Changuinola Power Plant	Diesel power plant

Table 1 (Continued)

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
Valle de Estrella, Costa Rica Earthquake 1991 (M7.4) (Cont.)	Limon Station	Telephone switching station
	Moin Power Plant	Diesel and gas turbine power plant
	RECOPE Refinery	Oil refinery
Sierra Madre, California Earthquake 1991 (M5.8)	Pasadena Power Plant	Five-unit gas-fired power plant
	Goodrich Substation	230 kV substation
Cape Mendocino Earthquakes 1992 (M7.0)	Pacific Mill	Lumber mill & Cogen plant
	Centerville Naval Base	HVAC and diesel power plant
	Humboldt Bay Power Plant	Two gas-fired units One nuclear unit (Inactive)
Landers & Big Bear Earthquakes 1992 (M7.4)	Cool Water Power Plant	Two gas-fired units Two combined cycle units
	SEGs 1 & 2 Steam Plants	Solar-powered generating plants
	Newberry Compressor Plant	Piston-driven gas compressors
	Pfizer Ore Processing	Limestone Production
	Mitsubishi Cement	Cement Production

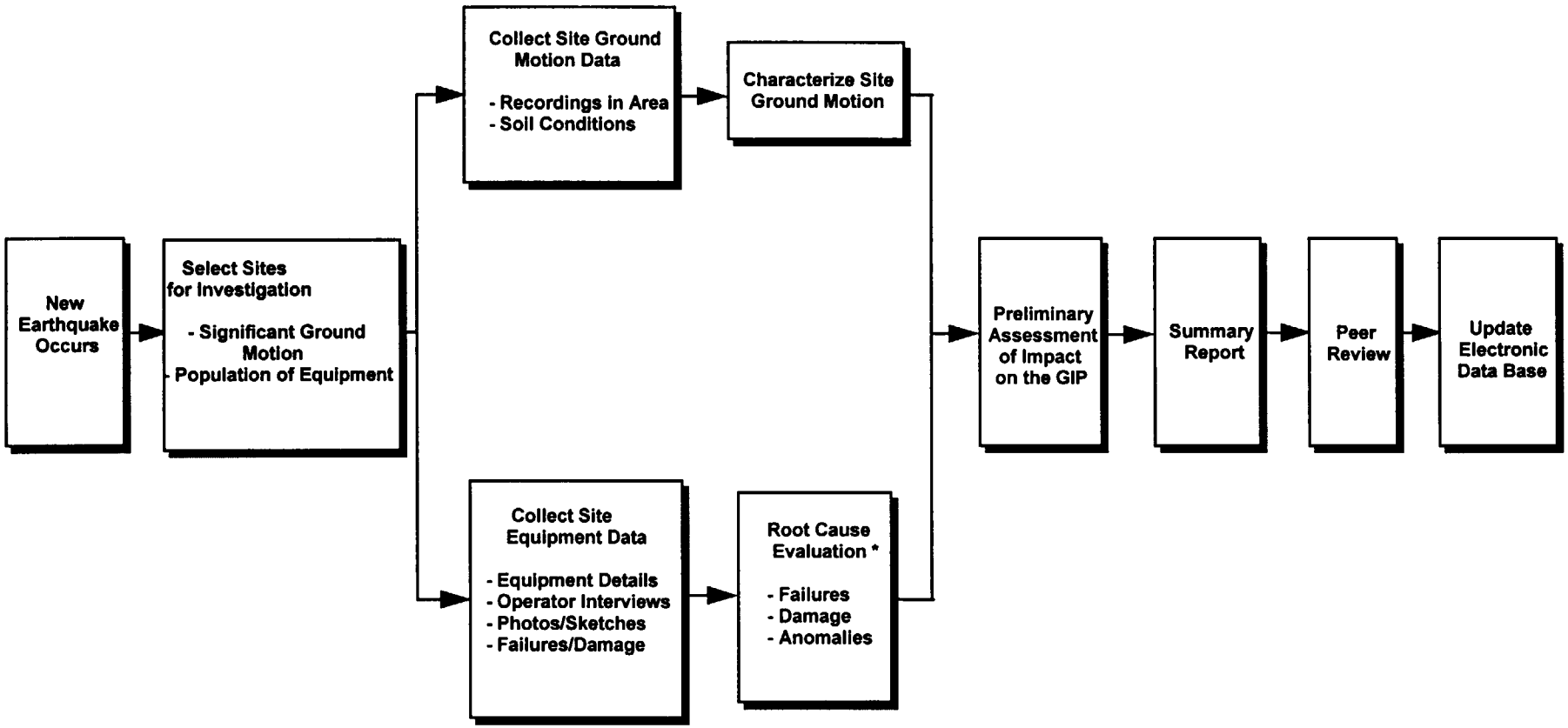
Table 1 (Continued)

SUMMARY OF SITES REVIEWED IN COMPILING THE SEISMIC EXPERIENCE DATABASE

Earthquake (Magnitude)	Facility	Type of Facility
Guam Earthquake 1993 (M8.0)	Cabras Power Plant	Two oil-fired units
	Piti Power Plant	Four oil-fired units
	Tanguisan Power Plant	Two oil-fired units
	Yigo Gas Turbine	Packaged gas turbine-generator
	Dededo Gas Turbine	Turbine-generator and diesels
	GPA Diesel Plants	Four units with two diesels each
	Uguma Water Treatment Plant	Water treatment facility
Northridge Earthquake 1994 (M6.7)	Sylmar/Rinaldi Station	Large electrical substation
	Olive View Cogen	Two-unit gas turbine plant
	Placerita Cogen	Two-unit gas turbine plant
	Financial Data Center	Data processing facility emergency diesel & UPS plant
	Valley Steam Plant	Two Unit (Active) Gas Fired Power Plant
	Castaic Pump-Turbine Plant	Seven-unit hydro plant

Figure 1

SQUG Data Collection and Validation Process



*Some information may impact the rules/caveats of the GIP and require GIP revisions. Revisions of the GIP are addressed in References 9 & 10.

Appendix A

Examples of Ground Motion Estimate Derivations

This appendix documents the development of earthquake response spectra at three SQUG database sites. The three sites are the PALCO Cogeneration Plant in Scotia, California; the Financial Data Center in Northridge, California; and three power generating facilities on the Island of Guam, Mariana Islands.

A.1 PALCO Cogeneration Plant (Scenario 2)

The PALCO Cogeneration Plant is located in the town of Scotia in Humboldt County, California. It is situated directly over the rupture plane of the April 25, 1992 moment-magnitude (M_w) 7.0 Petrolia (Cape Mendocino) earthquake. The Petrolia earthquake caused widespread damage throughout the Cape Mendocino region (Reagor and Brewer, 1992). It was assigned a maximum intensity of VIII on the Modified Mercalli Intensity Scale (MMI). Shaking effects consistent with MMI VIII were observed in Ferndale, Petrolia, Honeydew, Rio Dell, and Scotia. The mainshock was followed by two large aftershocks on April 26.

Strong-Motion Recordings

There was no strong-motion recording at the PALCO facility. The closest recording to the facility was 2.3 kilometers away at the Highway 101–Painter Street Overpass in the town of Rio Dell. The geographic coordinates of the recording site are 40.503°N latitude and 124.100°W longitude. The accelerograph is operated by the California Strong-Motion Instrumentation Program (CSMIP, Station #89324). The free-field accelerograph, which is located in an instrument shelter adjacent to the bridge, recorded peak ground accelerations of 0.55*g*, 0.39*g*, and 0.20*g* in the North, West, and Vertical directions, respectively (Shakal and others, 1992). The 5%-damped acceleration response spectra for the two horizontal components (Darragh and others, 1992) are shown in Figure A.1.

Earthquake Parameters

Oppenheimer and others (1993) report the following seismological parameters for the April 25 mainshock:

Date:	April 25, 1992
Time:	18:06:05 Greenwich Mean Time
Magnitude:	7.0 M_w
Epicenter:	40.332°N, 124.228°W
Depth:	10.6 km
Strike:	350° (northwest)
Dip:	13° to the northeast
Rake:	106° (predominantly thrust)

Similar source mechanisms were obtained by the U.S. Geological Survey (1992), Murray and others (1996), and Graves (1994).

Using strong-motion recordings, Graves (1994; written comm., 1994) determined the following rupture model for the earthquake:

Width (down-dip):	20 km
Length:	28 km
Depth to Top:	6.3 km
Strike:	350° (northwest)
Dip:	14° to the northeast
Rake:	90° to 105° for asperities (predominantly thrust) 115° to 140° for shallow southern part (oblique slip)
Average Slip:	1.9 m
Seismic Moment:	2.51×10^{26} dyne-cm (6.9 M_w)

The seismic moment of 2.51×10^{26} dyne-cm (dyne-centimeters) is consistent with a moment magnitude of 6.9 based on the moment-magnitude relationship of Hanks and Kanamori (1979).

The following distances from the recording site and the PALCO facility to the rupture plane of the Petrolia earthquake were calculated from the above rupture model and the epicentral coordinates determined by Oppenheimer and others:

Site	Epicentral Distance (km)	Azimuth (°)	Surface Distance (km)	Rupture Distance (km)
PALCO	19.8	33	7.3	13.3
CSMIP #89324	21.9	30	7.9	13.6

In this table, Rupture Distance is the shortest distance between the site and the rupture plane of the earthquake, Surface Distance is the shortest distance between the site and the surface projection of the rupture plane, and Azimuth is the angle between the epicenter and the site measured clockwise from North.

Local Site Conditions

Shakal and others (1992) describe the recording site as being underlain by 15 meters of alluvium. Heuze and Swift (1991) estimate the shear-wave velocity of the soil beneath the recording site to a depth of about 10 meters to be approximately 200 m/s (meters per second). There is no similar geotechnical data available for the PALCO facility. However, a 1:62,500 scale geologic map of the area (Ogle, 1953) indicates that both sites are located on relatively thin, young (Holocene) stream terrace deposits within the Eel River Valley. The terrace deposits are composed of gravel, sand, silt, and clay, with

gravel predominating. The Upper Pliocene Rio Dell Formation underlies the terrace deposits to a depth of several kilometers. Massive mudstone, alternating thin sandstone and mudstone, phantom-banded mudstone, and very fine-grained sandstone are the principal lithologic units of the Rio Dell Formation.

Based on the above information, both sites are consistent with Soil Profile Type S_D (Stiff Soil Profile) as defined in the 1997 Uniform Building Code (UBC; ICBO, 1997). This Soil Profile Type has shear-wave velocities in the top 30 meters that range between 180 to 360 m/s. Because of the similarity in the local site conditions, both the recording site and the PALCO site are considered to have similar soil-amplification characteristics.

Recommended Response Spectra

Based on the proximity of the PALCO facility and the Rio Dell recording (2.3 kilometers), the similar distance from both sites to the rupture plane of the Petrolia earthquake (13.3 and 13.6 kilometers), and the similar local soil and geological conditions at both sites, the Rio Dell recording can be used as a credible estimate of the ground motion at the PALCO Cogeneration Plant. The recommended 5%-damped acceleration response spectrum is shown in Figure A.2. This response spectrum is identical to that recommended by Boore (1997) for the same site.

A.2 Financial Data Center (Scenario 3)

The Financial Data Center is located in the city of Northridge in the San Fernando Valley, Los Angeles County, California. It is situated directly over the rupture plane of the January 17, 1994 moment magnitude (M_w) 6.7 Northridge earthquake. The earthquake caused widespread damage throughout the Los Angeles region (Dewey and others, 1995). It was assigned a maximum intensity of IX on the Modified Mercalli Intensity Scale (MMI). Shaking effects consistent with MMI IX were observed in Sherman Oaks, Northridge, Granada Hills, along the I-5 corridor just east of the Santa Susana Mountains, and in two neighborhoods of several blocks each in Santa Monica and west-central Los Angeles. Shaking effects consistent with MMI VIII were observed at many locations over a broad area of the San Fernando Valley, and also in parts of Santa Clarita, Simi Valley, Santa Monica, west-central Los Angeles, Fillmore, the University of Southern California/County Hospital complex in Los Angeles, and in a 3-kilometer long, several blocks wide, area of Hollywood along Hollywood Boulevard.

Strong-Motion Recordings

A single strong-motion recording was obtained on the roof of the Financial Data Center. There was no ground-level recording at the facility. There are, however, eleven ground-level recordings within 10 kilometers of the facility. The closest three recordings are on Roscoe Boulevard in Northridge. (LA Code #C130, 2.8 kilometers), Topanga Canyon Boulevard in Canoga Park (USC #53, 5.1 kilometers), and Saticoy Street in Northridge (USC #3, 5.5 kilometers). All three recordings are located close enough to the Financial Data Center to have experienced the same level of ground shaking and earthquake source effects.

The other eight recordings within 10 kilometers are not considered to be representative of the ground shaking at the Data Center for the following reasons. They were either

too far from the facility (greater than 8 kilometers), they were founded on significantly different geological deposits, or they experienced significant source directivity effects. These latter effects were particularly important for recordings located northeast of the Data Center in the direction of rupture propagation (see the discussion on source characteristics latter in this report).

Darragh and others (1995) and Trifunac and others (1994) give a detailed description of the three selected recordings. A summary of this information is provided in the following table.

Parameter	LA Code #130	USC #53	USC #3
Structure	7-story bldg.	1-story bldg.	2-story bldg.
Location	Ground level	Ground level	Ground level
Latitude	34.217°N	34.212°N	34.209°N
Longitude	118.553°W	118.606°W	118.517°W
Peak Ground Acceleration (g)	0.42 (North)	0.39 (S16W)	0.45 (South)
	0.41 (West)	0.35 (S74E)	0.33 (East)
	0.35 (Up)	0.42 (Up)	0.80 (Up)

The two horizontal components of the 5%-damped acceleration response spectra of the three selected recordings are shown in Figures A.3 to A.5.

Earthquake Parameters

Scientists of the U.S. Geological Survey and the Southern California Earthquake Center (1996) report the following seismological parameters for the earthquake:

Date:	January 17, 1994
Time:	12:30 Greenwich Mean Time
Magnitude:	6.7 M_w
Epicenter:	34.209°N, 118.541°W
Depth:	19 km
Strike:	N70°W to N80°W
Dip:	35° to 45° to the southwest
Mechanism:	Thrust

Similar source parameters were obtained by many other seismologists (e.g., BSSA, 1996). According to these studies, the rupture initiated at the hypocenter in the southeast corner of the rupture plane and propagated up-dip to the north and northeast where the largest subevent occurred.

Using strong-motion, teleseismic, GPS, and leveling data, Wald and others (1996) determined the following rupture model for the earthquake:

Width (down-dip):	21 km
Length:	14 km
Depth to Top:	6 km
Strike:	122° (Southeast)
Dip:	40° (Southwest)
Average Rake:	101° (thrust)
Average Slip:	1.3 m
Seismic moment:	$1.3 \pm 0.2 \times 10^{26}$ dyne-cm (6.7 M_w)
Average Stress Drop	74 bars

The following distances from the three recording sites and the Data Center to the rupture plane of the earthquake were calculated from the above rupture model and the epicentral coordinates determined by Scientists of the U.S. Geological Survey and the Southern California Earthquake Center (1996):

Site	Epicentral Distance (km)	Azimuth (°)	Surface Distance (km)	Rupture Distance (km)
Data Center	4.1	330	0.0	12.6
LA Code #C130	1.4	309	0.0	13.8
USC #53	6.0	273	1.4	15.8
USC #3	2.2	90	0.0	13.2

The distance measures in this table are the same as those defined previously for the PALCO facility.

Local Site Conditions

There are no reliable site-specific geotechnical data available for the Financial Data Center or the recording sites. A geologic map of the area (Yerkes and Campbell, 1993) indicates that the Financial Data Center and the USC #53 site are located on Holocene alluvium up to 30-meters thick and that the LA Code #C130 and USC #3 sites are located on Late Holocene alluvium up to 3-meters thick overlain by Holocene alluvium. Since it is likely that the buildings that house the accelerographs have foundations that are at least a few meters deep, any remaining Late Holocene deposits, if present at all, are too thin to have affected the recorded ground motions at frequencies less than about 25 Hz. Underlying the Holocene alluvium is a sequence of Quaternary, Tertiary, and Cretaceous sediments at least 1 to 2 kilometers thick.

Shear-wave velocity measurements were conducted at the USC recording stations using the CXW method. This method uses surface-wave dispersion to infer the shear-wave velocity profile at a site. However, Boore and Brown (1998) and Wills (1998) have shown that the CXW method can lead to estimates of shear-wave velocity that are significantly different than those obtained using more traditional down-hole and cross-hole techniques. Based on this conclusion, the CXW-based measurements are not used.

Instead of relying on direct shear-wave velocity measurements, the average shear-wave velocity in the top 30 meters of the Holocene alluvium that underlies the Data Center and three recording sites is estimated from shear-wave velocity characteristics determined for geologic units in California (Wills and Silva, 1998). This study found that the mean value of the average velocity in the top 30 meters of geologic units described as younger alluvium, Holocene alluvium, or undifferentiated Quaternary alluvium is 284 m/s. The standard error of this estimate is 85 m/s. According to this assessment, the Data Center and the three recording sites fall into Soil Profile Type S_D (Stiff Soil Profile) as defined in the 1997 UBC. This Soil Profile Type has a shear-wave velocity in the top 30 meters that ranges from 180 to 360 m/s. It was concluded based on the above information that the Data Center and the three recording sites have similar soil-amplification effects. The similarity in both the amplitude and shape of the response spectra from the three nearby recordings lends further empirical justification to this conclusion.

Recommended Response Spectrum

All of the recordings are located on the ground floor of 1-story to 7-story buildings. As a result, they are likely to be somewhat deficient in high-frequency ground motions due to wave-scattering and wave-passage effects. Further justification for these kinematic effects can be found by comparing the response spectrum for the LA Code #C130 recording, which was obtained in a 7-story building, with the two USC recordings, which were obtained in smaller 1-story and 2-story buildings (Figure A.6). The LA Code #C130 spectrum is found to be lower than the two USC spectra between frequencies of about 4 and 13 Hz. Because of this, the selected recordings, and especially the LA Code #C130 recording, are considered to be a conservative (i.e., lower) estimate of the high-frequency amplitude of the free-field spectra at each of these sites.

The three selected recordings are all located southeast and southwest of the Financial Data Center. A contour map of the 0.24-second spectral velocity developed by SAC Joint Venture Partnership (1995) suggests that short-period spectral amplitudes increased from south to north. This would suggest that the actual ground motion at the Center is likely to have been somewhat larger than indicated by these recordings.

Based on the proximity of the Financial Data Center and the three selected recordings (2.8 to 5.5 kilometers), the similar distance from each of the sites to the rupture plane of the Northridge earthquake (12.6 to 15.8 kilometers), the similar amplitude and spectral shapes of the three recorded response spectra (Figs. A.3 to A.5), and the similar local soil and geological conditions at each of the sites, the average of the LA Code #C130, USC #3, and USC #53 response spectra can be used as a credible, yet somewhat conservative (lower) estimate of the ground motion at the Financial Data Center. The recommended 5%-damped acceleration response spectrum is shown in Figure A.6.

Boore (1997) used three entirely different recordings to estimate a response spectrum at the Financial Data Center from the Northridge earthquake. The recordings he used were from the 7-story Hotel in Van Nuys (CSMIP #24386), the Sepulveda VA Hospital in Los Angeles (USGS #637), and the Rinaldi Receiving Station in Mission Hills (LADWP SMA-1 #5968). The latter two recordings were located northeast of the Financial Data Center and in the direction of rupture propagation. As a result, the ground motions at these two sites were larger than those located closer to the Center. For example, the horizontal peak accelerations at the Sepulveda VA Hospital were 0.94*g* and 0.74*g* and those at Rinaldi Receiving Station were 0.84*g* and 0.49*g*, significantly higher than those recorded at the three sites selected in this study.

The SAC Joint Venture Partnership (1995) also estimated ground motions from the Northridge earthquake for a site very close to the Financial Data Center (their Site 4). A comparison of the recommended response spectrum in Figure A.6 with that estimated by the SAC Joint Venture Partnership (1995) indicates that the SAC spectrum is higher, especially at high frequencies, than that recommended in this study. For example, SAC calculated peak accelerations of 0.71*g* (North) and 0.49*g* (South) for Site 4; whereas, a mean horizontal acceleration of 0.39*g* was estimated in the current study.

A.3 Guam Power Generating Facilities (Scenario 4)

The Guam Power Generating facilities are located on the Island of Guam, the largest and southernmost of the Marianas Island chain in the South Pacific. The island is approximately 48 kilometers long and between 6 and 19 kilometers wide. Guam is volcanic in origin. The southern end of the island is mountainous with altitudes ranging from 210 to 400 meters. The northern part of the island consists of a series of coral limestone terraces that are relatively flat and range from about 60 to 180 meters in height. The Guam power generating facilities consist of the Piti Power Plant and the Cabras Generating Station in the Apra Harbor area, and the Tanguisson, Yigo, and Dededo Generating Stations on the northern part of the island. According to EERI (1995), all of these facilities sustained some damage during the August 8, 1993 moment-magnitude (M_w) 7.7 Guam earthquake. The Apra Harbor facilities had the greatest amount of damage because of their location in an area of widespread ground-failure effects.

The power generating facilities are located several tens of kilometers northwest of the rupture plane of the Guam earthquake. According to U.S. Geological Survey (1993) and EERI (1995), the earthquake caused extensive damage to hotels in the Tumon Bay area. Many structures in the Apra Harbor area were seriously damaged due to liquefaction and related ground failure. Minor damage was widespread on the island. A relatively small tsunami was generated and was noted at several locations in the South Pacific, including Japan and Hawaii, with no reported damage. The earthquake was assigned a maximum intensity of IX on the Modified Mercalli Intensity Scale (MMI). Shaking effects consistent with MMI VII were observed at several locations on the northern part of the island (U.S. Geological Survey, 1993).

Strong-Motion Recordings

The United States Navy maintained three strong-motion instruments on Guam at the time of the earthquake, but no records were recovered from these instruments because

of malfunctions. However, EERI (1995) gives a qualitative estimate of the level of shaking on the island from an evaluation of liquefaction effects and damage to concrete bus stops. This evidence supports the conclusion that effective ground accelerations on the island probably ranged from 0.15*g* to 0.25*g*.

Earthquake Parameters

The U.S. Geological Survey (1993) reports the following seismological parameters for the earthquake:

Date:	August 8, 1993
Time:	08:24:25 Greenwich Mean Time
Magnitude:	7.1 m_b, 8.0 M_s
Epicenter:	12.982°N, 144.801°E
Depth:	59 km
Strike:	255° (southwest)
Dip:	20° northwest
Rake:	90° (thrust)

From a complete study of P and SH body waves, Campos and others (1996) relocated the aftershocks and the subevents of the mainshock and proposed a relatively simple model of the rupture process of the event. Based on this analysis, they conclude that the earthquake ruptured a shallow-dipping thrust fault that corresponds to the subduction interface of the Pacific and Philippine Sea plates. Campos and others' best single point-source model for the earthquake based on the inversion of teleseismically observed body waves is as follows:

Seismic Moment:	4.5×10^{27} dyne-cm (7.7 M_w)
Centroid Depth:	41.5 km
Strike:	241.67° (southwest)
Dip:	13.77° northwest
Rake:	84.91° (predominantly thrust)

The moment magnitude (M_w) given by this inversion is 7.7 according to the moment-magnitude relationship of Hanks and Kanamori (1979). The fault plane solutions reported by Dziewonski and others (1994), the U.S. Geological Survey (1993), and the California Institute of Technology (Caltech) are all quite different from each other and from the solution given above. Campos and others show that their solution is statistically superior to the these other solutions because they used better constrained body-wave data.

Distances from the power generating facilities to the rupture plane of the earthquake were computed from the rupture model derived by Campos and others (1996). This rupture model indicates that the earthquake started with a small foreshock located at the hypocenter. This foreshock was about 8.6 seconds in duration and had a low rate of

moment release. Then the first major subevent occurred about 30 kilometers to the northeast of the epicenter at a depth of around 46 kilometers. This was followed by a second major subevent about 12 seconds later that was located 48 kilometers to the northeast of the first subevent. The entire source-rupture process was finished in less than 32 seconds. This model indicates that 42% of the moment release occurred during the first subevent and 57% occurred during the second subevent. Campos and others give the following parameters for this rupture model:

Width (down-dip):	50 km
Length:	100 km
Centroid Depth:	46 km (first subevent); 37 km (second subevent)
Strike:	240° (southwest)
Dip:	12.5° northwest
Rake:	89° (thrust)
Average Slip:	2.53 m (first subevent); 3.47 m (second subevent)
Seismic Moment:	4.5×10^{27} dyne-cm (7.7 M_w)
Stress Drop:	118 bars

Campos and others show that the above rupture model is consistent with the distribution of aftershocks and provides a very good fit to the coseismic displacements estimated at various locations on Guam from Global Positioning System (GPS) surveys conducted before and after the earthquake by Beavan and others (1994). Campos and others also found that this rupture model was generally consistent with, but provided a better fit to the GPS displacements, than rupture models proposed by Abe (1994) and Tanioka and others (1995), which were based on an inversion of Tsunami waveforms from Japanese tidal gauge stations.

The following distances from the Tanguisson, Yigo, and Dededo facilities to the rupture plane of the earthquake were calculated from the above rupture model and the epicentral coordinates determined by the U.S. Geological Survey (1993):

Site	Epicentral Distance (km)	Azimuth (°)	Energy Center Distance (km)	Rupture Distance (km)
Tanguisson	60.8	0.4	68.5	66.0
Yigo	65.1	8.9	67.3	64.1
Dededo	59.5	3.8	66.1	63.7

In the above table, Energy Center Distance is the distance from the site to the energy center of the rupture as defined by Crouse (1991). All other distance measures are the same as those defined previously for the PALCO facility. Consistent with the definition of the energy center given by Crouse (1991), the location of this center was placed at the location of the moment centroid of the first, closest subevent. However, rather than

use the independently estimated depth of this centroid, the more conservative estimate of 42.4 kilometers, which represents the projection of the subevent onto the modeled rupture plane, was preferred. Distances for the Piti and Cabras facilities were excluded from this analysis for the reasons specified below.

Local Site Conditions

EERI (1995) describes the Piti and Cabras facilities as being underlain by soft soils. The Piti facility is described as being located on loose coral fill underlain by lagoonal and estuarine deposits. The Cabras facility is reported to be founded on loose coral fill over a coral reef. The presence of soft soils and the occurrence of ground failure at the Piti and Cabras facilities indicates that they should be classified as Soil Profile Type S_F as defined in the 1997 UBC. Sites in this soil category require site-specific investigations to determine their dynamic soil-response characteristics. As a result, it is not possible to reliably estimate the ground motions at these facilities without performing a dynamic site-response analysis using site-specific geotechnical information.

There are no site-specific geotechnical information for the Tanguisson, Yigo, and Dededo sites. Instead, the local site conditions at these facilities were determined from a 1:50,000-scale geology map of Guam (Tracey and others, 1964). According to this map, the Tanguisson facility is underlain by reef facies of the Pliocene and Pleistocene Mariana Limestone. This unit is a massive, generally compact, porous and cavernous white limestone of reef origin. The Yigo site is underlain by detrital facies of the Mariana Limestone. This unit is a friable to well-cemented, coarse-to-fine grained, generally porous and cavernous white detrital limestone, mostly of lagoonal origin. The Dededo facility is underlain by the Miocene and Pliocene Barrigada Limestone. This unit is a massive, well-lithified to friable medium-to-coarse grained white foraminiferal limestone.

As reported by Dames & Moore (1994), various geophysical investigations have been performed to investigate the physical nature and configuration of the volcanic rocks and limestone on the island. Of particular interest are seismic refraction surveys and gravity surveys performed in 1982 by the Guam Environmental Protection Agency. The results of these studies indicate that the seismic velocities in the upper part of the limestone are relatively low. The surface layer of limestone, between 30 and 38 meters thick, has an average compressional-wave velocity of 945 m/s. According to Dames & Moore, this corresponds to an estimated shear-wave velocity of 460 m/s. Below the upper layer of limestone is a second limestone layer with an average compressional-wave velocity of 2,040 m/s and an estimated shear-wave velocity of 915 m/s. The volcanic basement beneath the second limestone layer has an average compressional-wave velocity of about 2,835 m/s.

The shear-wave velocity in the upper limestone layer is within the lower half of the range of shear-wave velocities (360 to 760 m/s) that are used to define Soil Profile Type S_C (Very Dense Soil and Soft Rock) in the 1997 UBC. However, considering that the shear-wave velocities reported by Dames & Moore (1994) represent an average of many measurements, it is possible that some of these sites had shear-wave velocities that fell within the upper part of Soil Profile Type S_D (180 to 360 m/s; Stiff Soil Profile). Because of this uncertainty, It is concluded that the Tanguisson, Yigo, and Dededo sites can be classified as either Soil Profile Types S_D or S_C.

Recommended Response Spectrum

Because of the lack of strong-motion recordings, It was necessary to develop a quantitative estimate of ground shaking at the Guam power generating facilities using the following empirical attenuation relationships developed from strong-motion recordings of subduction earthquakes worldwide: Kawashima and others (1984, 1986), Annaka and Nozawa (1988), Crouse (1991), Dames & Moore (1994), Molas and Yamazaki (1995, 1996), and Youngs and others (1997). Each of these attenuation relationships requires a set of specific earthquake parameters in order for them to be applied correctly. Magnitude measures include moment magnitude M_w and Japan Meteorological Agency (JMA) magnitude M_j. Distance measures include epicentral distance, closest distance to the rupture plane, and distance to the energy center of the earthquake. Also required for some relationships are the focal depth, the depth to the closest part of the fault rupture, and the type of subduction event (interplate or intraslab).

The earthquake parameters used to estimate the ground motions from each of the attenuation relationships are given in the following table.

Parameter	Crouse	Youngs et al.	Kawashima et al.	Annaka & Nozawa	Molas & Yamazaki
Magnitude Measure	7.7 M_w	7.7 M_w	7.6 M_j	7.6 M_j	7.6 M_j
Distance Measure	Distance to Energy Center	Closest Distance to Rupture	Epicentral Distance	Closest Distance to Rupture	Closest Distance to Rupture
Focal Depth (km)	41.5	41.5	—	41.5	41.5
Source Type	—	Interface ($Z_T = 0$)	—	—	—
Component	Average Horizontal	Average Horizontal	Resultant Horizontal	Average Horizontal	Largest Horizontal
Site Conditions	Firm Soil & Rock	Soil & Rock	Firm Soil & Rock	V_s = 300 to 600 m/s	Hard Soil & Rock

In the above table, the value of M_w was estimated from the seismic moment of 4.5×10^{27} dyne-cm determined by Campos and others (1996) using the moment-magnitude relationship of Hanks and Kanamori (1979). The value of M_j was estimated from the average of the estimates calculated from the seismic moment versus M_j relationships published by Sato (1979) and Satoh and others (1997) using a seismic moment of 4.5×10^{27} dyne-cm. An estimate of the average horizontal component of ground motion was calculated from the amplitude of the resultant horizontal component and the largest horizontal component by applying the frequency-dependent ratios developed by Ansary and others (1995).

So as not to give undue influence to the attenuation relationships that are based on Japanese strong-motion recordings only, the three Japanese relationships were given the same cumulative weight as the other attenuation relationships in the calculation of a weighted average ground motion. The estimated average horizontal value of PGA

calculated from each of the five attenuation relationships for each generic site condition, along with the weighted average from the five relationships, is summarized in the following table. Figures A.7 and A.8 show the corresponding 5%-damped acceleration response spectra for the Tanguisson facility.

Facility	Kawashima et al. (1/9 wgt.)	Annaka & Nozawa (1/9 wgt.)	Crouse; Dames & Moore (1/3 wgt.)	Molas & Yamazaki (1/9 wgt.)	Youngs et al. (1/3 wgt.)	Weighted Average
Tanguisson						
Rock	0.151	0.165	0.127	0.090	0.130	0.130
Firm Soil	0.195	0.165	0.216	0.095	0.208	0.187
Yigo						
Rock	0.143	0.171	0.129	0.093	0.134	0.131
Firm Soil	0.184	0.171	0.219	0.099	0.213	0.190
Dededo						
Rock	0.154	0.173	0.130	0.094	0.135	0.133
Firm Soil	0.198	0.173	0.222	0.100	0.214	0.193

Note that the range of weighted averages of the PGA estimates (0.130*g* to 0.193*g*) is generally consistent with the range of effective accelerations estimated by EERI (1995) from an evaluation of liquefaction effects and damage to bus stops (0.15*g* to 0.25*g*).

Inspection of Figures A.7 and A.8 indicate that the estimated spectral accelerations on rock are lower than those on firm soil at all frequencies. Because of the uncertainty in the classification of the sites into one of the 1997 UBC Soil Profile Types, the lower estimates for rock, which are consistent with Soil Profile Type S_C, were used to conservatively estimate the expected response spectrum at the three facility sites.

Because of the similarity in the estimated ground motions for the three facility sites, the more conservative (lower) ground motions on rock calculated for the Tanguisson site were used as a credible yet somewhat conservative (lower) estimate of the ground motion at the Tanguisson, Yigo, and Dededo power generating facilities. The recommended 5%-damped acceleration response spectrum is shown in Figure A.9. There is insufficient geotechnical information to develop recommended response spectra for the Piti and Cabras facilities.

References

Abe, K. (1994). "Tsunami Source Model of the 1993 Mariana Earthquake," abstract, *Eos Transactions of AGU*, vol. 75, Western Pacific Geophysics Meeting Supplement, p. 64.

Annaka, T., and Y. Nozawa (1988). "A Probabilistic Model for Seismic Hazard Estimation in the Kanto District, " *in* Proceedings, Ninth World Conference on Earthquake Engineering, August 29, 1988, Tokyo-Kyoto, Japan, vol. II, p. 107-112.

Ansary, M.A., F. Yamazaki, and T. Katayama (1995). "Statistical Analysis of Peaks and Directivity of Earthquake Ground Motion," *Earthquake Engineering and Structural Dynamics*, vol. 24, p. 1527-1539.

Beavan, J., I. Murata, S. Nakao, T. Kato, K. Hirahara, T. Tanaka, R. Abad, C. Scholz, S. Roecker, and D. Davis (1994). "Determination of the Philippine Sea Plate Velocity From Global Positioning System Observations, and Effects of the 1993 Guam Earthquake," abstract, *Eos Transactions of AGU*, vol. 75, Western Pacific Geophysics Meeting Supplement, p. 59.

Boore, D.M. (1997). "Estimates of Average Spectral Amplitudes at FOAKE Sites," *in* An Evaluation of Methodology for Seismic Qualification of Equipment, Cable Trays, and Ducts in ALWR Plants by Use of Experience Data, Appendix C, U.S. Nuclear Regulatory Commission, Report No. NUREG/CR-6464, p. C1-C69.

Boore, D.M., and L.T. Brown (1998). "Comparing Shear-Wave Velocity Profiles from Inversion of Surface-Wave Phase Velocities with Downhole Measurements: Systematic Differences Between the CXW Method and Downhole Measurements at Six USC Strong-Motion Sites," *Seismological Research Letters*, vol. 69, no. 3, p. 222-229.

BSSA (1996). "Special Issue on the Northridge, California Earthquake of January 17, 1994," Teng, T.-L., and K. Aki, eds., *Bulletin of the Seismological Society of America*, vol. 86, no. 1B.

Campos, J., R. Madariaga, and C. Scholz (1996). "Faulting Process of the August 8, 1993, Guam Earthquake: A Thrust Event in an Otherwise Weakly Coupled Subduction Zone," *Journal of Geophysical Research*, vol. 101, no. B8, p. 17,581-17,596.

Crouse, C.B. (1991). "Ground-Motion Attenuation Equations for Earthquakes on the Cascadia Subduction Zone, " *Earthquake Spectra*, vol. 7, p. 201-236.

Dames & Moore (1994). "Earthquake Hazard Vulnerability Study, Guam, Mariana Islands," report prepared for the Government of Guam Civil Defense/Emergency Services Office by Dames & Moore, Los Angeles, December.

Darragh, R., M. Huang, T. Cao, V. Graizer, and A Shakal (1995). "Los Angeles Code-Instrumented Building Records from the Northridge, California Earthquake of January 17, 1994: Processed Release No. 2," California Strong Motion Instrumentation Program, California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, Report No. OSMS 95-07.

Darragh, R., T. Cao, C. Cramer, M. Huang, and A. Shakal (1992). "Processed CSMIP Strong-Motion Data from the Cape Mendocino/Petrolia Earthquake of April 25, 1992: Release No. 1," California Strong Motion Instrumentation Program, California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, Report No. OSMS 92-12.

Dewey, J.W., B.G. Reagor, L. Dengler, and K. Moley (1995). "Intensity Distribution and Isoseismal Maps for the Northridge, California, Earthquake of January 17, 1994," *U.S. Geological Survey Open-File Report 95-92.*

Dziewonski, A., G. Ekstrom, and M. Salganik (1994). "Centroid-Moment Tensor Solutions for July-September 1993," *Physics of the Earth and Planetary Interiors*, vol. 83, p. 165-174.

EERI (1995). "Guam Earthquake of August 8, 1993, Reconnaissance Report," Comartin, C.D., ed., *Earthquake Spectra*, vol. 11, supplement B, Earthquake Engineering Research Institute, Oakland, California, Publication No. 95-02.

Graves, R.W. (1994). "Rupture History and Strong Ground Motion Modeling of the 1992 Cape Mendocino Earthquake," abstract, *Seismological Research Letters*, vol. 65, no. 1, p. 40.

Hanks, T.C., and H. Kanamori (1979). "A Moment Magnitude Scale," *Journal of Geophysical Research*, vol. 84, no. B5, p. 2348-2350.

Heuze, F.E., and R.P. Swift (1991). "Seismic Refraction Studies at the Painter Street Bridge Site, Rio Dell, California," Lawrence Livermore National Laboratory, Livermore, California, Report No. UCRL-ID-108595.

ICBO (1997). "The Uniform Building Code, 1997 Edition," International Conference of Building Officials, Whittier, California.

Kawashima, K., K. Aizawa, and K. Takahashi (1984). "Attenuation of Peak Ground Motion and Absolute Acceleration Response Spectra, " *in* Proceedings, Eighth World Conference on Earthquake Engineering, July 21-28, 1984, San Francisco, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, vol. II, p. 257-264.

Kawashima, K., K. Aizawa, and K. Takahashi (1986). "Attenuation of Peak Ground Acceleration, Velocity and Displacement Based on Multiple Regression Analysis of Japanese Strong Motion Records," *Earthquake Engineering and Structural Dynamics*, vol. 14, p. 199-215.

Molas, G.L., and F. Yamazaki (1995). "Attenuation of Earthquake Ground Motion in Japan Including Deep Events, " *Bulletin of the Seismological Society of America*, vol. 85, p. 1343-1358.

Molas, G.L., and F. Yamazaki (1996). "Attenuation of Response Spectra in Japan Using New JMA Records, " *Bulletin of the Earthquake Resistant Structure Research Center*, vol. 29, p. 115-128.

Murray, M.H., G.A. Marshall, M. Lisowski, and R.S. Stein (1996). "The 1992 Cape Mendocino, California, Earthquake: Coseismic Deformation at the South End of the Cascadia Megathrust," *Journal of Geophysical Research*, vol. 101, no. B8, p. 17,707-17,725.

Ogle, B.A. (1953). "Geology of Eel River Valley Area, Humboldt County, California," State of California, Department of Natural Resources, Division of Mines, *Bulletin 164*, San Francisco.

Oppenheimer, D., G. Beroza, G. Carver, L. Dengler, J. Eaton, L. Gee, F. Gonzales, A. Jayko, W.H. Li, M. Lisowski, M. Magee, G. Marshall, M. Murray, R. McPherson, B. Romaniwicz, K. Satake, R. Simpson, P.G. Somerville, R. Stein, and D. Valentine (1993). "The Cape Mendocino, California Earthquake Sequence of April, 1992: Subduction at the Triple Junction," *Science*, vol. 261, p. 433-438.

Reagor, B.G. and L.R. Brewer (1992). "The Cape Mendocino Earthquakes of April 25 and 26, 1992," *U.S. Geological Survey Open-File Report 92-575.*

SAC Joint Venture Partnership (1995). "Technical Report: Characterization of Ground Motions During the Northridge Earthquake of January 17, 1994," Report No. SAC 95-03.

Satoh, T., H. Kawase, and T. Sato (1997). "Statistical Spectral Model of Earthquakes in the Eastern Tohoku District, Japan, Based on the Surface and Borehole Records Observed in Sendai," *Bulletin of the Seismological Society of America*, vol. 87, no. 2, p. 446-462.

Sato, R. (1979). "Theoretical Basis on Relationships Between Focal Parameter and Earthquake Magnitude," *Journal of Physics of the Earth*, vol. 27, p. 353-372.

Scientists of the U.S. Geological Survey and the Southern California Earthquake Center (1996). "The Magnitude 6.7 Northridge, California, Earthquake of 17 January 1994," *Science*, vol. 266, p. 389-397.

Shakal, A., R. Darragh, M. Huang, T. Cao, R. Sherbourne, R. Syndor, P. Malhotra, C. Cramer, J. Wampole, P. Fung, and C. Petersen (1992). "CSMIP Strong-Motion Records from the Petrolia, California Earthquakes of April 25-26, 1992," California Strong Motion Instrumentation Program, California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, Report No. OSMS 92-05.

Tanioka, Y., K. Satake, and L. Ruff (1995). "Tsunami Excitation and Mechanism of the Guam Earthquake, August 8, 1993," *Pure and Applied Geophysics*, vol. 110, p. 64.

Tracey, J.I., S.O. Schlanger, J.T. Starr, D.B. Doan, and H.G. May (1964). "General Geology of Guam," *U.S. Geological Survey Professional Paper 403-A.*

Trifunac, M.D., M.I. Todorovska, and S.S. Ivanovic (1994). "A Note on Distribution of Uncorrected peak Ground Accelerations During Northridge, California, Earthquake of 17 January 1994," *Soil Dynamics and Earthquake Engineering*, vol. 13, no. 3, p. 1987-1996.

U.S. Geological Survey (1992). "Preliminary Determination of Epicenters Monthly Listing, April 1992," U.S. Department of Interior, Geological Survey, National Earthquake Information Center, Denver, Colorado.

U.S. Geological Survey (1993). "Preliminary Determination of Epicenters Monthly Listing, August 1993," U.S. Department of Interior, Geological Survey, National Earthquake Information Center, Denver, Colorado.

Wald, D.J., T.H. Heaton, and K.W. Hudnut (1996). "The Slip History of the 1994 Northridge, California, Earthquake Determined from Strong-Motion, Teleseismic, GPS, and Leveling Data," *Bulletin of the Seismological Society of America*, vol. 86, no. 1B, p. S49-S70.

Wills, C.J. (1998). "Differences in Shear-Wave Velocity Due to Measurement Methods: A Cautionary Note," *Seismological Research Letters*, vol. 69, no. 3, p. 216-221.

Wills, C.J., and W. Silva (1998). "Shear-Wave Velocity Characteristics of Geologic Units in California," *Earthquake Spectra*, vol. 14, no. 3, p. 533-556.

Yerkes, R.F., and R.H. Campbell (1993). "Preliminary Geologic Map of the Canoga Park 7.5′ Quadrangle, Southern California," *U.S. Geological Survey Open-File Report 93-206.*

Youngs, R.R., S.-J. Chiou, W.J. Silva, and J.R. Humphrey (1997). "Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes", *Seismological Research Letters*, vol. 68, p. 58-73.

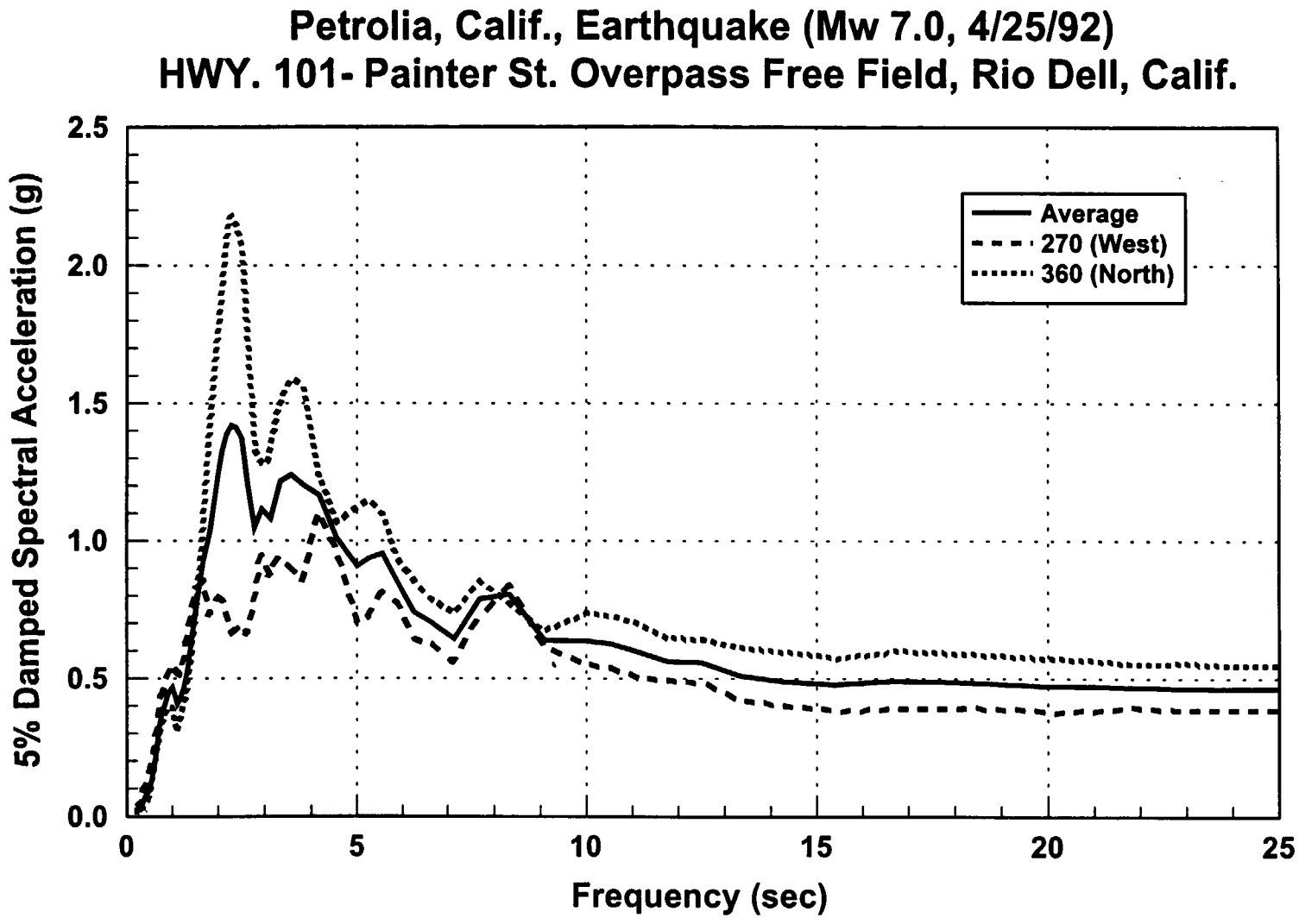

Petrolia, Calif., Earthquake (Mw 7.0, 4/25/92)
HWY. 101- Painter St. Overpass Free Field, Rio Dell, Calif.
5% Damped Spectral Acceleration (g)
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
Frequency (sec)
Average
270 (West)
360 (North)

Figure A.1

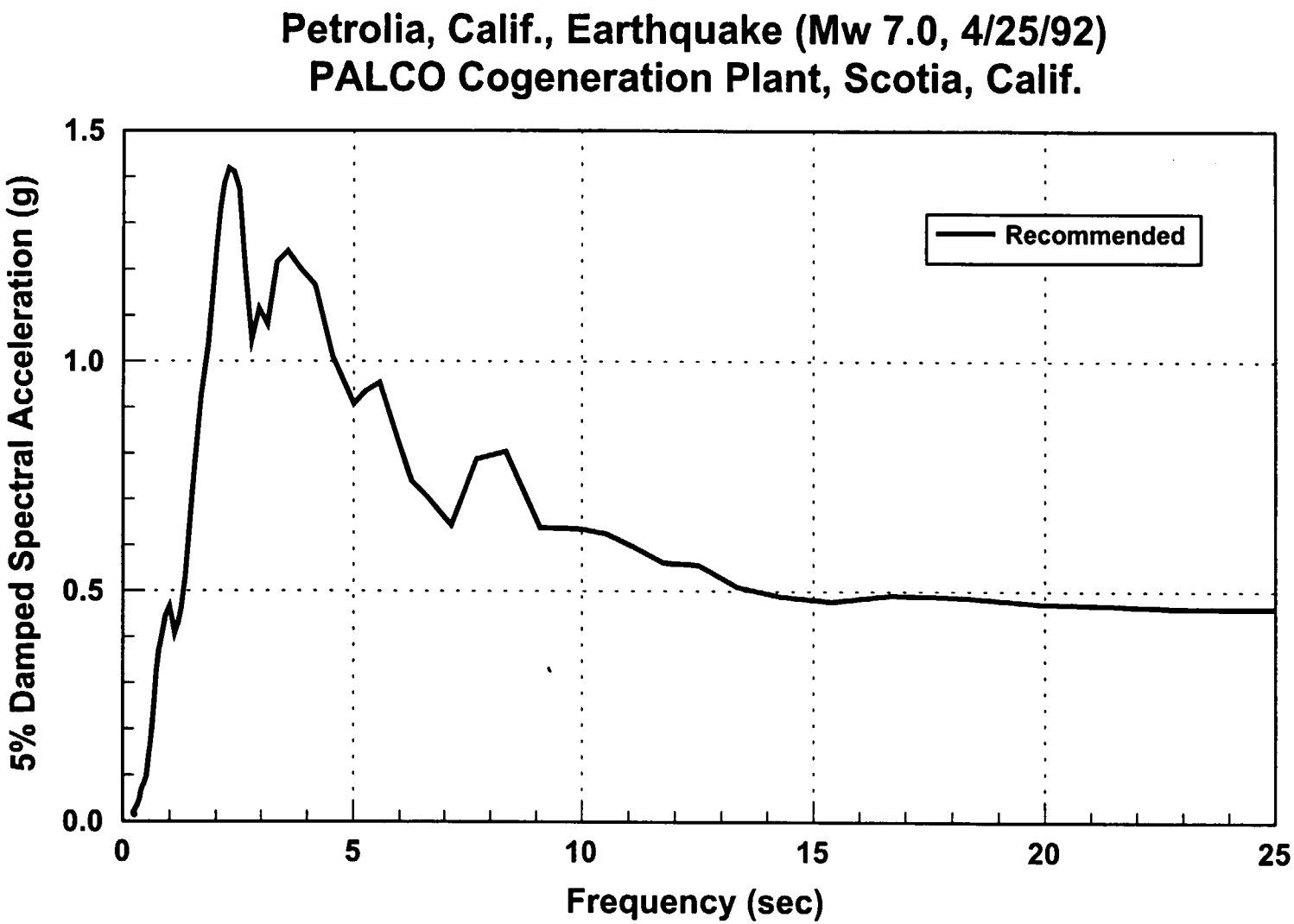

Petrolia, Calif., Earthquake (Mw 7.0, 4/25/92)
PALCO Cogeneration Plant, Scotia, Calif.
5% Damped Spectral Acceleration (g)
1.5
1.0
0.5
0.0
0
5
10
15
20
25
Frequency (sec)
Recommended

Figure A.2

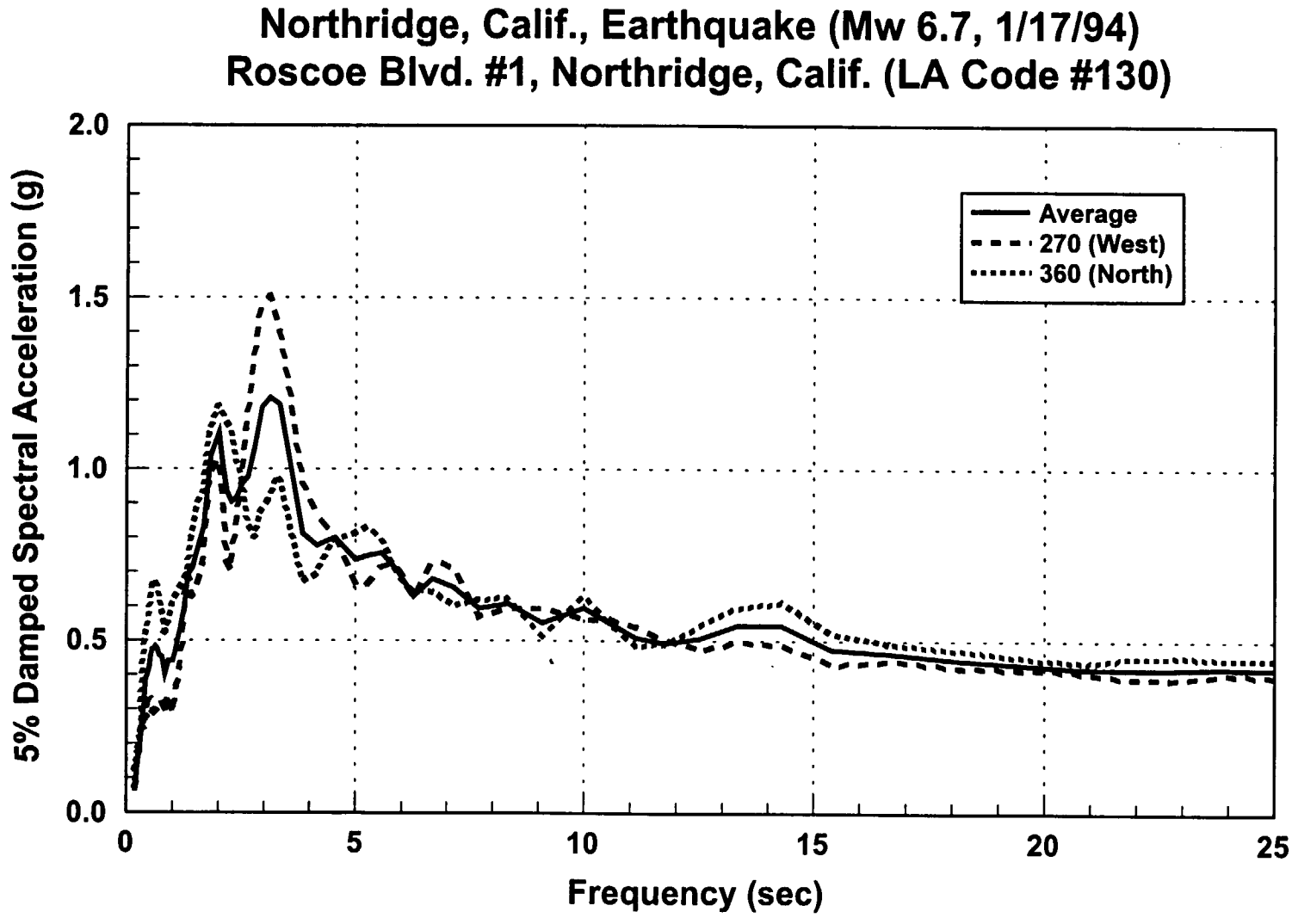

Northridge, Calif., Earthquake (Mw 6.7, 1/17/94)
Roscoe Blvd. #1, Northridge, Calif. (LA Code #130)
5% Damped Spectral Acceleration (g)
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
Frequency (sec)
Average
270 (West)
360 (North)

Figure A.3

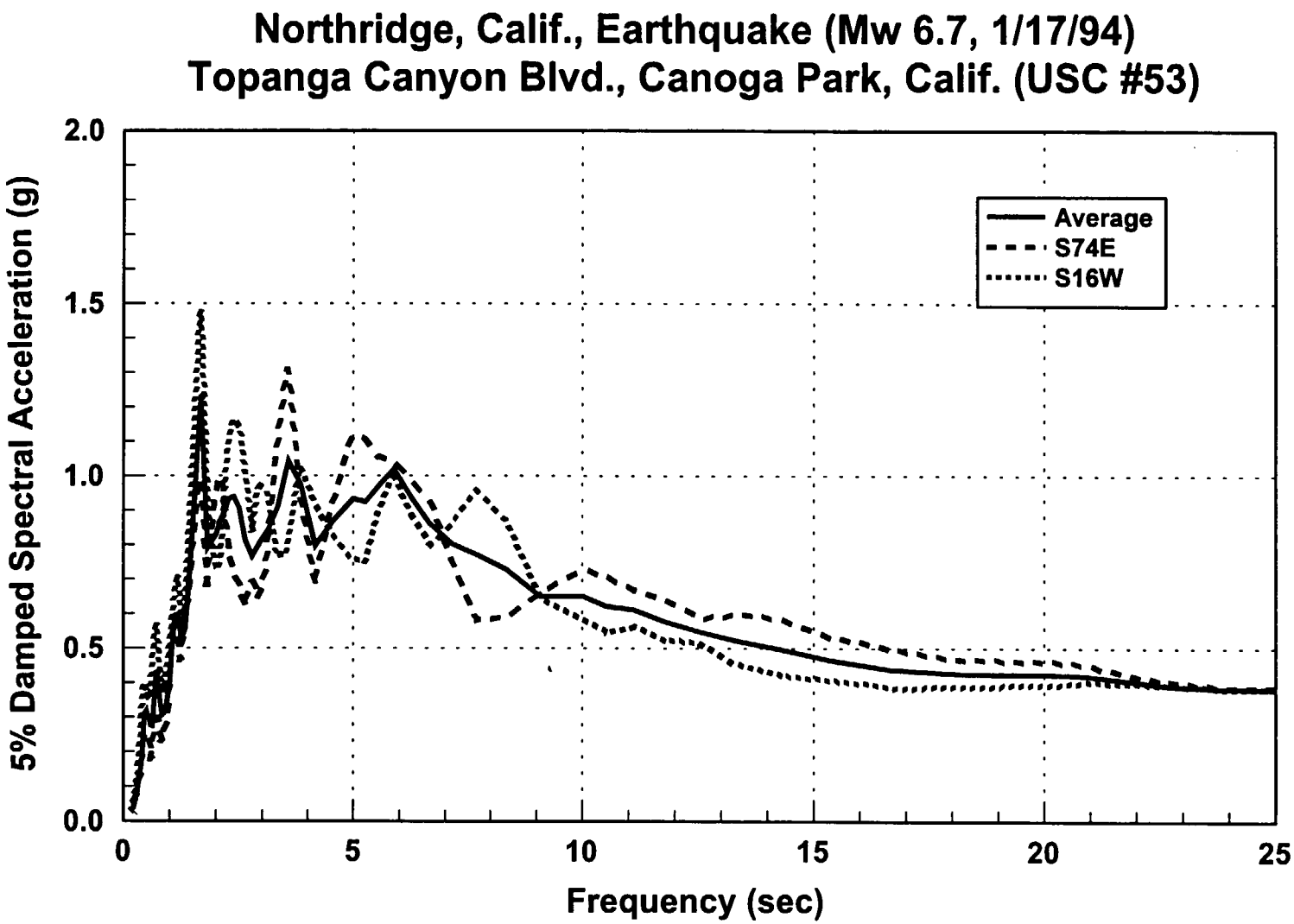

Northridge, Calif., Earthquake (Mw 6.7, 1/17/94)
Topanga Canyon Blvd., Canoga Park, Calif. (USC #53)
5% Damped Spectral Acceleration (g)
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
Frequency (sec)
Average
S74E
S16W

Figure A.4

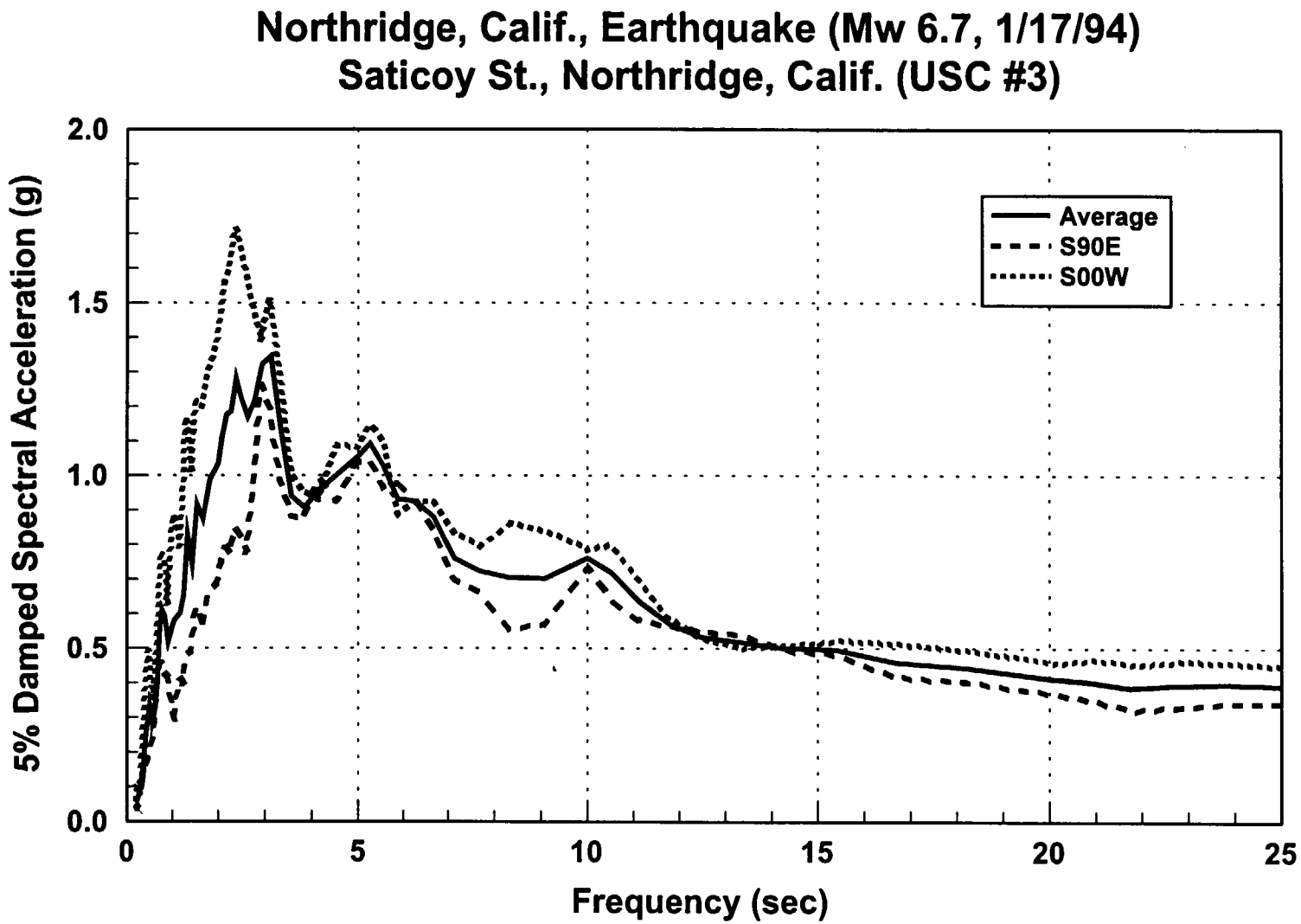

Northridge, Calif., Earthquake (Mw 6.7, 1/17/94)
Saticoy St., Northridge, Calif. (USC #3)
5% Damped Spectral Acceleration (g)
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
Frequency (sec)
Average
S90E
S00W

Figure A.5

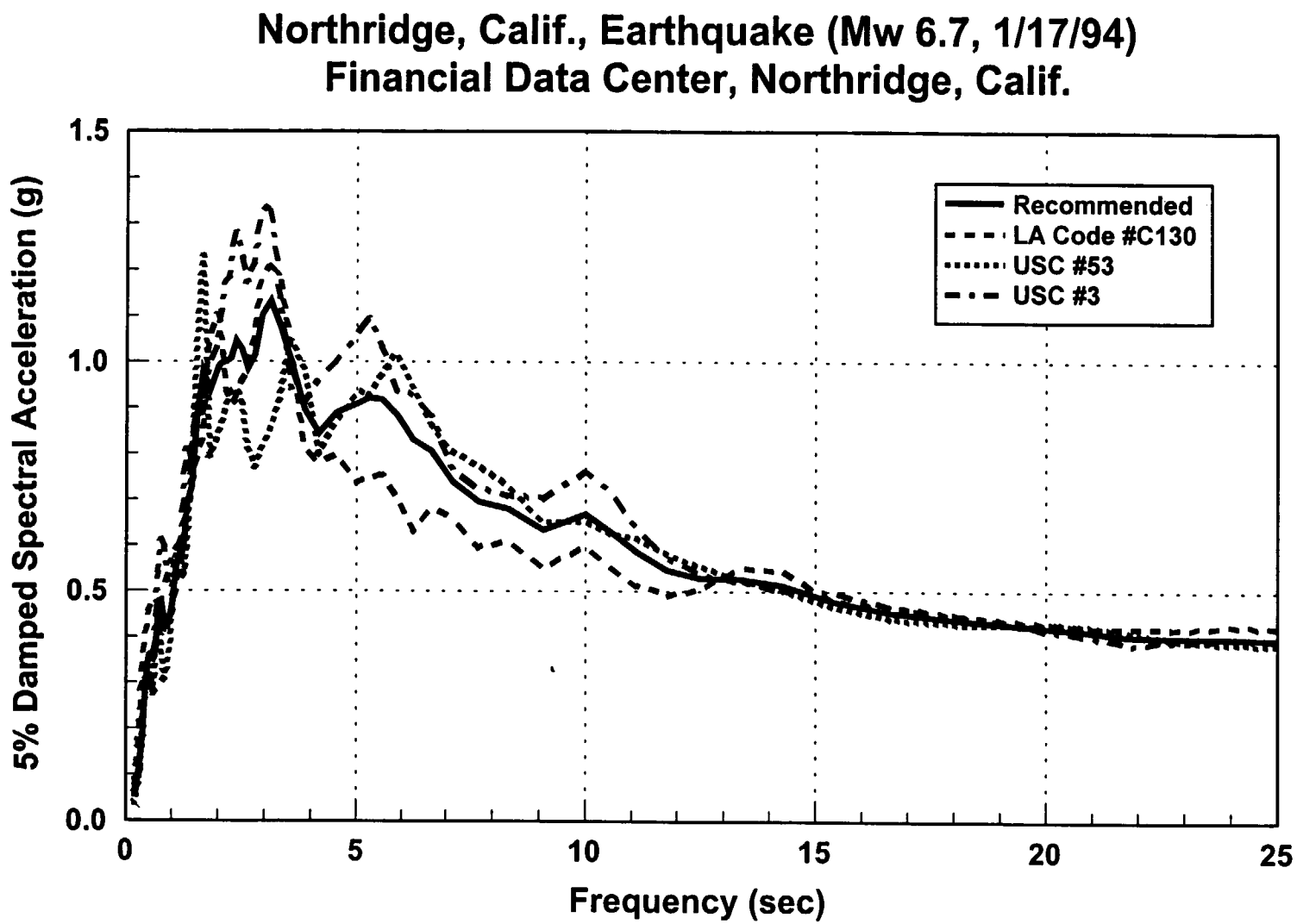

Northridge, Calif., Earthquake (Mw 6.7, 1/17/94)
Financial Data Center, Northridge, Calif.
5% Damped Spectral Acceleration (g)
1.5
1.0
0.5
0.0
0
5
10
15
20
25
Frequency (sec)
Recommended
LA Code #C130
USC #53
USC #3

Figure A.6

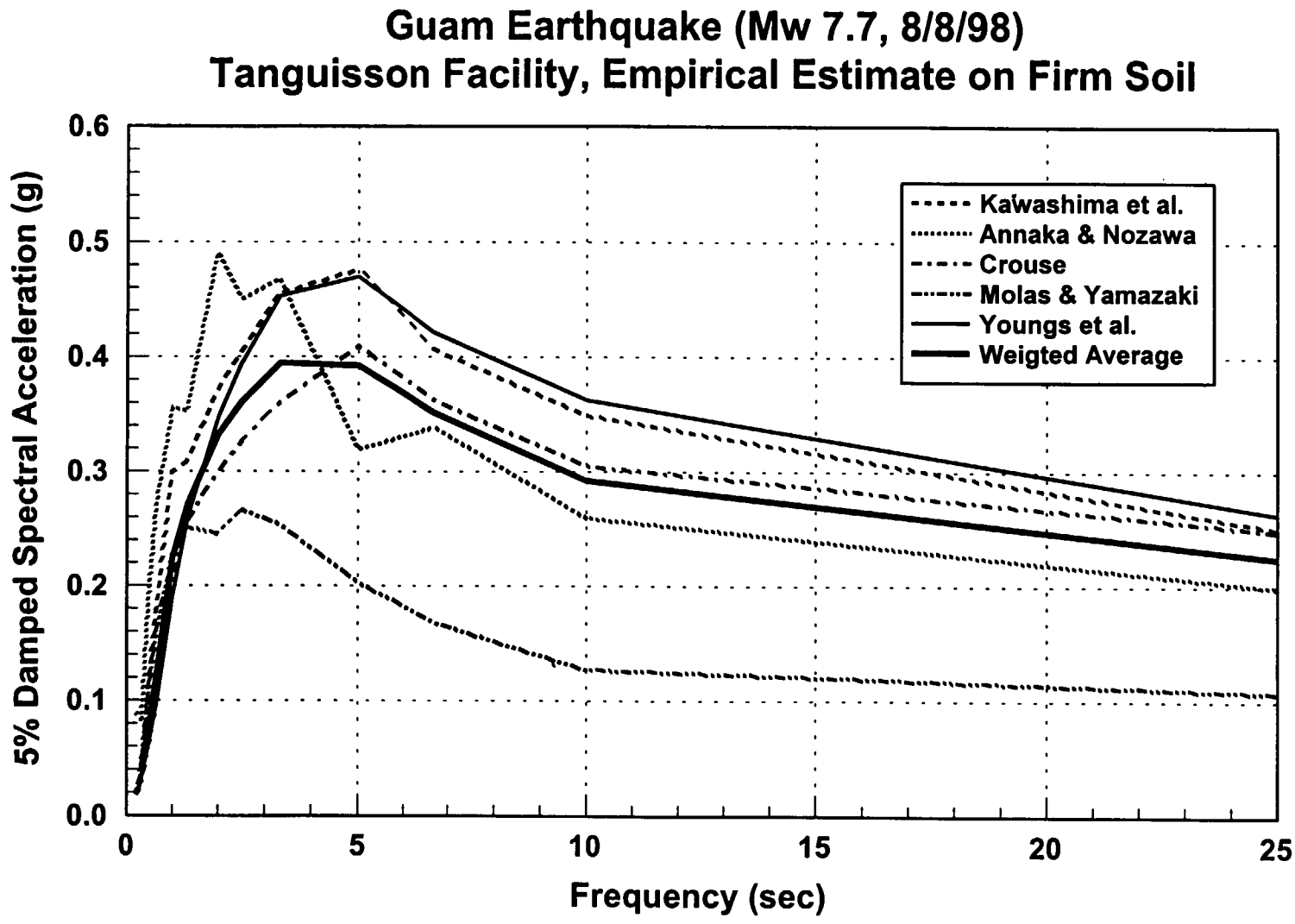

Guam Earthquake (Mw 7.7, 8/8/98)
Tanguisson Facility, Empirical Estimate on Firm Soil
5% Damped Spectral Acceleration (g)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
Frequency (sec)
Kawashima et al.
Annaka & Nozawa
Crouse
Molas & Yamazaki
Youngs et al.
Weigted Average

Figure A.7

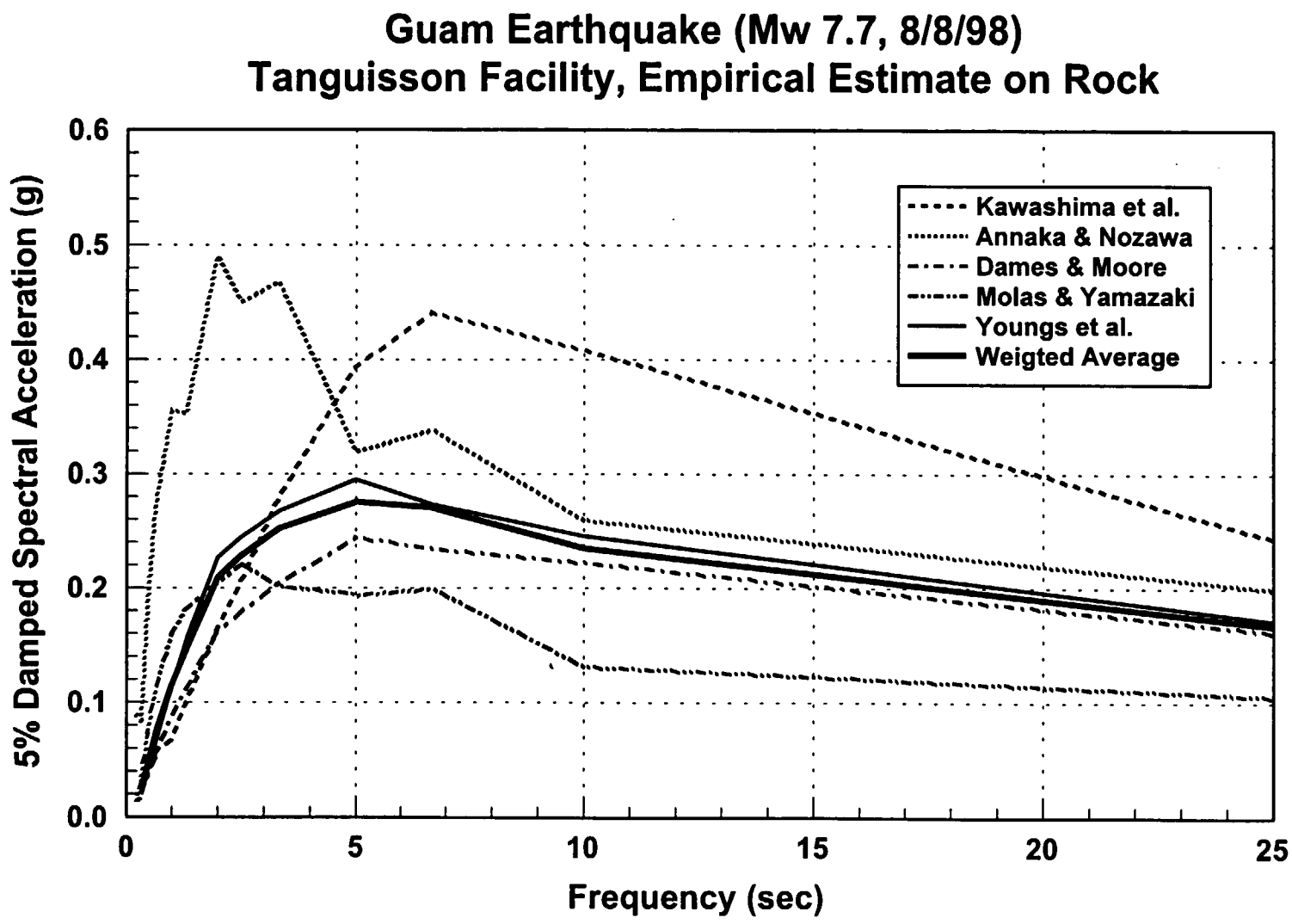

Guam Earthquake (Mw 7.7, 8/8/98)
Tanguisson Facility, Empirical Estimate on Rock
5% Damped Spectral Acceleration (g)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
Frequency (sec)
Kawashima et al.
Annaka & Nozawa
Dames & Moore
Molas & Yamazaki
Youngs et al.
Weigted Average

Figure A.8

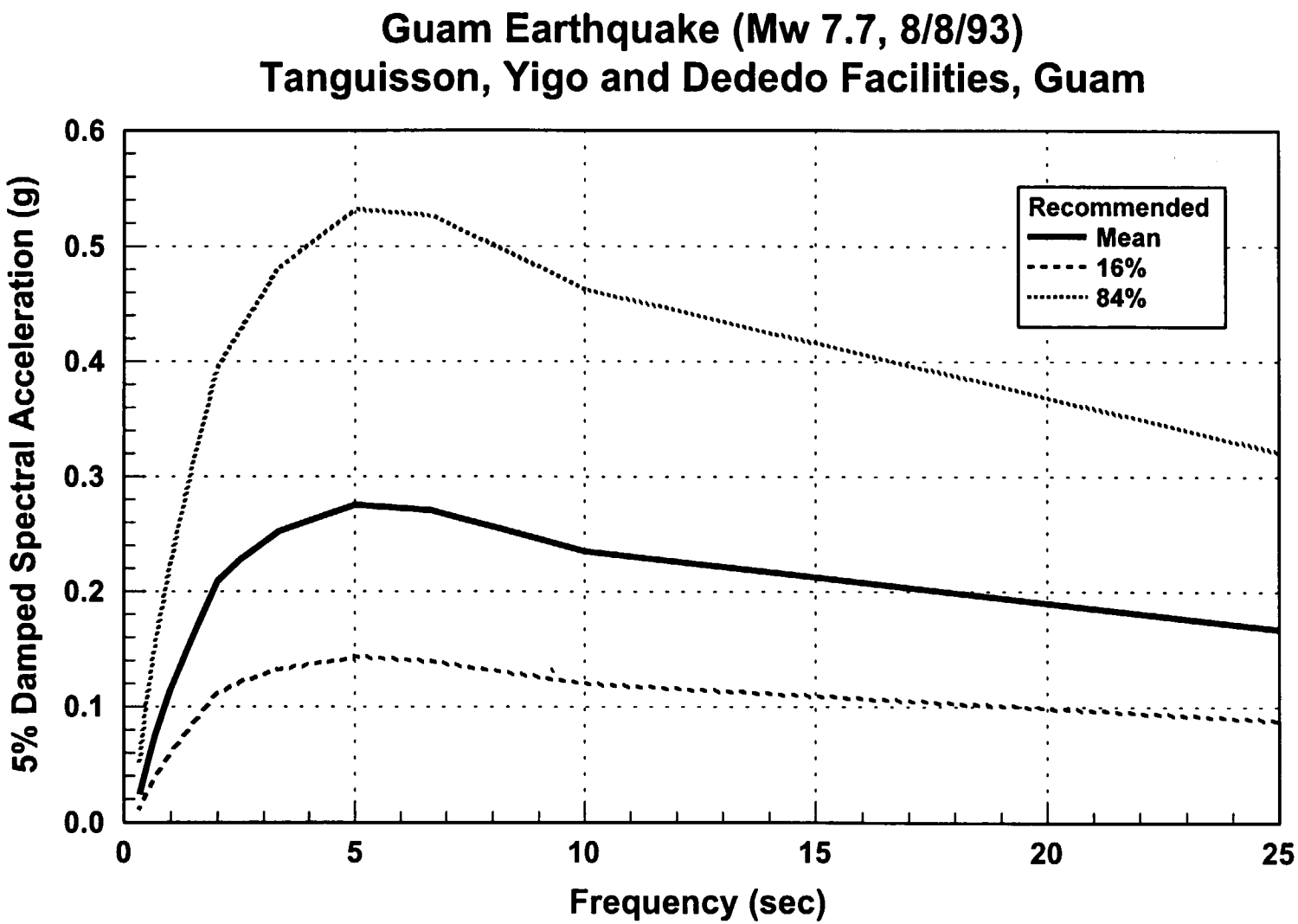

Guam Earthquake (Mw 7.7, 8/8/93)
Tanguisson, Yigo and Dededo Facilities, Guam
5% Damped Spectral Acceleration (g)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
Frequency (sec)
Recommended
Mean
16%
84%

Figure A.9