Keynote Paper

Seismological Considerations for the Analysis of Soil Structure Interaction

Gail M. Atkinson, Canada Research Chair in Earthquake Hazards and Ground Motions, Dept. Earth Sciences, University of Western Ontario

There are several significant seismological issues to consider in the analysis of soil structure interaction (SSI) effects of nuclear power plants (NPP). Typically, a seismic hazard analysis will be used to define free-field motions at the plant site; the free-field motions are then used in engineering analyses to infer the motions that will be input to the foundation mat (the SSI analysis). Thus the seismological input to the problem is most fundamentally the definition of appropriate free-field motions to input to the SSI problem. These motions are usually defined as three-component time histories that "match" or otherwise represent a target Uniform Hazard Spectrum (UHS) for the site, for the desired probability level. Several general issues arise in defining these time histories: Should they be "real" (previously-recorded) time histories, or are simulated records acceptable? What record characteristics are most important? How many records should be used? How should they be matched to the UHS: tight or loose matching? matching of the entire UHS with a single broadband record or use of multiple scenarios? There are also specific issues that are crucial for nuclear power plants: How should we model the high-frequency motions expected for plants on rock sites in eastern North America (and similar environments)? How might high-frequency motions be filtered out by considering incoherence across the foundation mat? This presentation overviews these issues and provides comments and recommendations.

Ground motion characteristics for sites in eastern North America will be used to illustrate the issues under consideration, including in particular the high-frequency content of eastern motions. Typical UHS shapes and how they arise will be described, and the means by which the UHS might be matched using real records discussed. Time histories and response spectra for actual eastern earthquakes will be presented in the context of typical eastern UHS. Records from the June 2010 M5.0 earthquake in western Quebec, plus records from the 2005 M4.7 earthquake in Charlevoix, Quebec, the 1988 M5.8 Saguenay, Quebec earthquake and the 1985 M6.7 Nahanni, NWT earthquake will be used to illustrate the characteristics of eastern ground motions and their implications. The manner in which such motions should be "scaled up" to represent severe low-probability earthquake shaking will be addressed.

Session – Introduction Papers

Keynote Paper

Seismic Soil-Structure Interaction Analysis: A Walk Through Time – Past, Present, and Future

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Seismic soil-structure interaction (SSI) analysis of nuclear power plant (NPP) structures has evolved significantly over the last 50 years. Initially SSI was treated in the same manner as machine vibrations. This approach evolved into simple soil spring models applied in the late 1960s and early 1970s. More sophisticated continuum mechanics approaches came on stage at the same time as finite element methods entered the field of SSI analysis. Significant controversy was present in this time frame as practitioners attempted to benchmark analysis methods by purely analytical means. This need for benchmarking of SSI analysis methods with experimental and actual earthquake data was readily apparent in the 1980s, which led to experiments, such as Lotung and Hualien in Taiwan. These scale model experiments, in conjunction with others, and the recording of strong motion earthquakes in the free-field and in NPP structures led to increased confidence in analysis methodologies and advancement in the state-of-practice. These approaches evolved into three-dimensional sub-structuring approaches prevalent in the field today. Regulatory evolution followed technical evolution, sometimes very closely, in other cases somewhat behind in time. This paper will present the time line and highlight one view of important events over the past 50 years.

The elements of SSI (free-field ground motion definition, soil material modeling, structure modeling, and SSI analysis procedures and parameters) will be discussed with emphasis on their inter-relationship. The definition of free-field ground motion (frequency content, spatial variation of motion) is intimately coupled with SSI analysis procedures. The state-of-practice of soil material modeling continues to be equivalent linear, but significant effort may be devoted to nonlinear material behavior in the future. Structure model development has evolved to very detailed and sophisticated finite element models – how are these to be treated in the SSI analysis. Other aspects of the SSI phenomena, such as linear-nonlinear representations, and structure-to-structure interaction, will be discussed.

Future developments will be hypothesized, especially the inter-relationship between performance-based seismic design criteria and the calculation of seismic demand for NPP structures, systems, and components (SSCs).

These topics will be discussed in light of the current trends in seismic hazard assessments; earthquake ground motion characteristics, such as, high frequency ground motion; standard designs of NPPs (designated Certified Designs in the US); observed seismic response of NPPs subjected to strong earthquake ground motions; and specialized needs for the definition of seismic demand of SSCs for applications such as probabilistic safety assessments (SPSAs), and risk informed decision-making.

Session – Introduction Papers

US Regulatory Lessons Learned from New NPP Applications on Implementation of SSI Evaluation

Bret Tegeler, Samir Chakrabarti and Manas Chakravorty - US NRC NRO/DE/SEB

The objective of this paper is to discuss recent lessons learned from the review of new Nuclear Power Plant (NPP) applications from a regulatory and licensing perspective. Particular emphasis will be made on the implementation of General Design Criteria (GDC) 2 for NPP, Appendix A and Earthquake Engineering Criteria for NPP, Appendix S to US Code of Federal Regulations (CFR) 10CFR50, as it applies to evaluating new NPP Category I Structures Systems and Components (SSCs) for Safe Shutdown Earthquake (SSE) considering the effect of Soil-Structure Interaction (SSI). The paper first will discuss applicable US regulations related to Design Certification (DC), Combined Operating License (COL) applications, establishing the SSE for the site, and the evaluation of SSCs for an SSE level earthquake. Secondly, it will discuss briefly the implementing guidance of CFRs as specified in the Standard Review Plan (SRP), Regulatory Guides (RG), and Interim Staff Guidance (ISG). Finally, it will discuss the issues that the US NRC staff, as a result of its review of new applications, is observing as to level of detail provided by the applicants in the application and the staff's need for additional information to verify effective implementation and to make appropriate safety determination.

Session – Introduction Papers

Keynote Paper

SSI Effects of Kashiwazaki-kariwa NPP at NCO (Niigataken Chuetsu-Oki) Earthquake in 2007

Takao Nishikawa (Professor emeritus, Tokyo Metropolitan University), Shohei Motohashi, Hiroto Inoue (Japan Nuclear Energy Safety Organization)

In 16th July 2007, Niigataken Chuetsu-Oki (NCO) earthquake occurred and attacked Kashiwazaki-Kariwa NPP site of Tokyo Electric Power Company in Japan. In this earthquake, earthquake motions were recorded at base-mats and upper floors of every reactor buildings (7 units, BWR Mark-II type: 5 units and ABWR type: 2 units) in the site. Though the observed earthquake motions in the buildings were 2 - 3 times over the design earthquake motions, all of 7 units were safely shutdown. These observed earthquake data were very valuable for evaluating the actual building behaviour including SSI effect against the earthquake motion. Using these observed data, simulation analyses of the reactor buildings were conducted based on 3-dimensional FEM models for the buildings and the surrounding soils.

All of the reactor buildings at the Kashiwazaki-Kariwa site are deeply embedded in the ground. Soils under the buildings are soft rock (shear wave velocity: about Vs=400m/s) and soils around the side of the building are backfilled by sand. And one side of every reactor building is adjacent to turbine building with 2 - 3m gap. The structure of the reactor building is made of reinforced concrete and main seismic elements are shield (cylindrical) wall and inner/outer box walls symmetrically arranged on the fairly stiff base-mat, and these walls are connected at upper floor slabs.

3-dimensional FEM models of typical units were constructed for the reactor buildings and their surrounding soils in which also considered adjacent turbine buildings. Physical constants such as concrete and soil properties, etc. were set based on as actual data as possible. However, as the nonlinearity behavior (stiffness degradation) of the backfill soil under the earthquake motion was not known well, parameter study was conducted. Using these models, the simulation analyses were conducted by earthquake response analysis based on the observed earthquake motions at the building. Input motions to the models were the observed motions at the base-mat of the buildings. And analytical response motions at the upper floors were compared with the observed motions.

As the result, 3-dimensional FEM model simulated well the observed earthquake motions. And it is understood that the stiffness degradation of backfill soil surrounding the building affected to the reactor building behavior as SSI effect and that the adjacent turbine building also affected to the reactor building behavior as SSSI (structure-soil-structure interaction) effect. Moreover, it is clarified that flexibility of the upper floor slab of the building affects to the floor responses of different positions of the same floor level.

Session – Introduction Papers

The Simulation of the KK7 Reactor Building Structural Response for NCO 2007 Event Using Different Modelling and Analysis Techniques

Pentti Varpasuo (Fortum Nuclear Services Ltd)

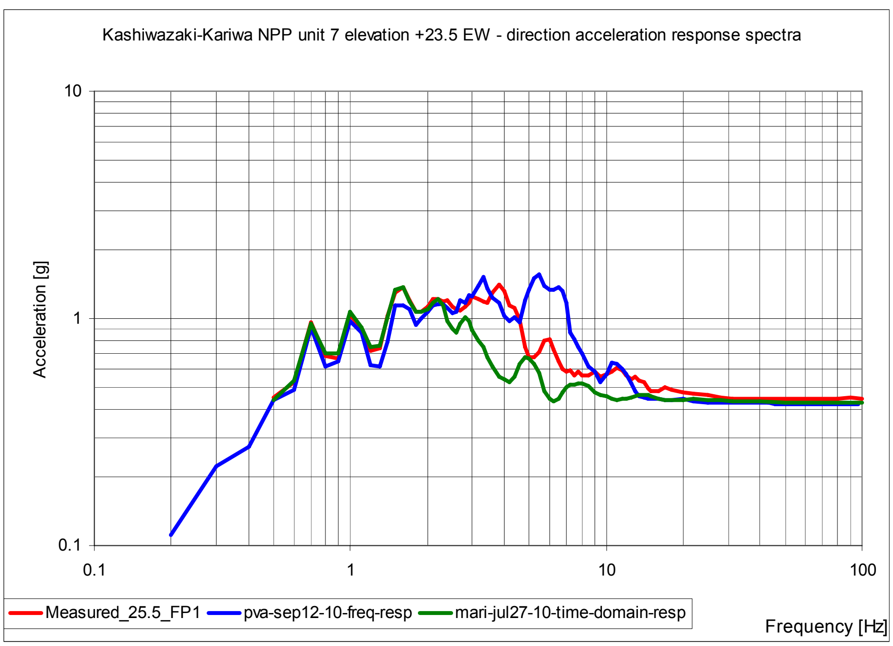
Key words: soil-structure interaction, seismic excitation, structural response

In this paper the combined soil-structural analysis of the Kashiwazaki-Kariwa nuclear power plant unit 7 for the Niigata-ken-Chuetsu-oki earthquake of 2007.

All input data considering the earthquake excitation, soil and structural properties and reactor building lay-out has been obtained from TEPCO in the framework of KARISMA benchmark, which is a part of IAEA extra-budgetary project "Seismic safety of existing nuclear power plants".

In the analysis the reactor building structures have been modelled using stick, shell and solid 3D models the foundation impedances for the reactor building have been calculated with the of SASSI program. The structural response for the elevation +23.5 in the reactor building has been carried out with the aid of both time domain analysis and frequency domain analysis using the ABAQUS/STANDARD and NASTRAN programs.

The comparison of the preliminary simulated response with the measured response of the elevation +23.5 in the reactor building calculated by both analysis methods and using the 3D shell model has been given in EW -direction in Figure 1:



References: MSC/NASTRAN, Quick reference manual, McNeal-Schwendler Corp., Los Angeles, 2009.

Session – Methodologies and Frameworks

Overview of Evidence on Model Uncertainty in Soil-Structure Interaction Studies

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The influence of model uncertainty was largely neglected in early stages of development of the Theory of Structural Reliability and as a direct consequence it remains virtually ignored in structural design codes and in engineering practice in general. Perhaps one of the first coordinated efforts to gather data on the subject was due to CIGRÉ (1992), which promoted studies on transmission line towers that preceded a renewed interest on the effect of model uncertainty on design and resulting reliability estimates of structural systems. By model uncertainty it is herein understood the variability of the predictions of the static or dynamic response of a fully defined structural system subjected to an equally completely defined excitation, by the particular model, computer program and assumptions adopted by the designer.

If model uncertainty is quantified by the coefficient of variation (CV) of the design estimate, it has been repeatedly observed in Round Robin experiments and elsewhere that in linear systems subjected to static loads the CV is rarely much lower than 5% and increases significantly for dynamic loading and in presence of system non-linearities, such as yielding or fracture, reaching in those cases values that may exceed 20%. Thus, in certain cases, model uncertainty may be more relevant in the decision making process than the uncertainties concerning the excitation or the system properties.

Soil-structure interaction studies or, in general, the assessment of the influence of the upper soil layers on the seismic excitation of Nuclear Power Plant (NPP) structures, are expected to be characterized by large model uncertainty and hence are expected to be in the last group. Perhaps equally relevant is the proneness of human error in both areas, which may also affect the resulting reliability of the system under consideration. Within this context, the author presents one case study related to the determination of the seismic response spectra for a brazilian NPP and also an assessment of the estimation error associated to the widely accepted assumption of vertically propagating shear waves.

On the basis of the available evidence, the author finally suggests tentative recommendations for the consideration of model uncertainty in soil-structure interaction studies.

Key-Words: Soil-structure interaction, Surface spectra, Model Uncertainty, Reliability, Vertical wave propagation.

Session – Methodologies and Frameworks

Framework for Design of Base-Isolated Next-Generation Nuclear Facility Structures

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Seismic isolation response modification technology has been used for buildings and non-building structures for more than forty years. Advances in this technology (new materials, development of new motion isolation and damping devices, advances in combating aging, and improved analysis methods) have supported deployment of base isolation systems for increasingly more complex structures and higher levels of seismic performance. The effectiveness of these systems in real earthquakes has demonstrated their value, and has motivated research and development of even more advanced, more economical, and longer-lived systems.

Building of new nuclear power plants in the US has already started. Simultaneously, commercial development of the next generation of nuclear power plants in North America is imminent. There are strong indications that nuclear power plant vendors are considering base isolation options for their designs. The motivation for such choice is the ability to standardize the design above the isolation plane and, thus, significantly accelerate the permitting and the construction process to, improve the economy of the new plants while maintaining the required levels of seismic safety and performance.

A review of the base isolation technology applicable to heavy and stiff non-building structures such as nuclear power plants is presented first. This review focuses on the significant work in this area conducted in 1980s and 1990s in the US, Japan and France. Benefits, such a decrease in the seismic energy transmitted to the main structure and systems and components therein, and limitations, such as deformation limits, vertical motion transmission, and durability, of the technologies now in use are discussed. Next, tools for assessment of seismic performance of base isolated nuclear power plant structures are presented. The ability to accurately model the seismic response of heavy and stiff base isolated structures, including their interaction with the supporting soil, is crucial for understanding their behavior and for demonstrating the safety of such structures. Finally, the elements of a performance-based risk-informed design framework for base isolated nuclear facility structures, capable of addressing the fragility of the structures and the systems and components contained in them, are presented. Such design framework will provide the regulators with tools to quantify the seismic safety margin afforded by seismic isolation, and enable comparative evaluation of different conventional and isolated structures as well as different seismic isolation technologies.

Session – Methodologies and Frameworks

Soil-Structure Interaction Involving Nonlinear Soil Response

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Nonlinear soil response greatly complicates dealing effectively with soil-structure interaction and the difficulties are compounded by the almost universal practice of separating the foundation system for the superstructure, dealing with each one separately and then trying to piece them together to get the final response. This process often uses procedures based on assumptions that ignore significant consequences of interaction. This paper reviews some of these procedures and assumptions and quantifies their reliability by comparison with results from combined analyses of structure-soil foundation systems.

As an example of the kind of topics the paper will present, lets us consider what is regarded as the state of the art for dealing with large and very important bridges on pile foundations which follows the practice outlined above. The pile foundation is analyzed separately with the objective of getting the time history of seismic motions at the pile cap and a 6x6 stiffness matrix to represent the constraints of the pile foundation on superstructure response. These objectives can only be achieved correctly, if the system is elastic, but fall short, if the soil response is strongly nonlinear. The analysis of the soil-foundation alone only includes kinematic interaction. When the soil response in nonlinear, the inertial effects of the superstructure drive further the displacements of the soils and increases the effects of nonlinearity causing a much softer system This effect which can be shown to be significant is completely neglected when the stiffness of the pile foundation is evaluated with no reference to inertial interaction.

But this is only one aspect of the problems associated with getting reliable pile stiffnesses. The 6x6 pile cap stiffness of the foundation is not determined under dynamic conditions but is estimated by a static push- over analysis to an arbitrary displacement level. There is no documented procedure for selecting this displacement – it appears to be always 2 inches. Is this an effective constant value stiffness for represent the time history of stiffnesses resulting from the changing time-histories of seismic displacements during earthquake shaking?. The paper describes a dynamic procedure for evaluating an effective constant stiffness matrix.

The paper will examine other troublesome aspects of nonlinear soil-structure interaction (some involving tall buildings) with the aim of presenting a comprehensive view of what goes on during seismic excitation. Such a picture could serve as a guide for evaluating the appropriateness of candidate simpler methods.

Session – Methodologies and Frameworks

A Macro-Element for a Shallow Foundation to Simulate Soil-Structure Interaction

Stéphane Grange, Georges Nahas, Jean-Mathieu Rambach (IRSN)

In earthquake engineering, the quality of the soil is important for determining the seismic response of the structure. Nevertheless, in current seismic design approach, plastic hinging into the soil and mobilization of bearing capacity are too often neglected. Several approaches exist to take into account Soil-Structure Interaction (SSI): the following work is based on the “macro-element” concept. The particularity of the macro-element lies in the fact that the movement of a foundation is entirely described by a system of generalised variables (forces and displacements) defined at the foundation centre. The non linear behaviour of the soil is reproduced using the classical theory of plasticity. The uplift behaviour of the foundation which is a geometric non-linearity is also taken into account according to the plasticity theory. The macro-element has been implemented into FedeasLAB, which is a Matlab toolbox developed at UC Berkeley and in the finite element code Cast3m developed by CEA/IRSN as a free user material. Comparisons with experimental results of a foundation submitted to static, cyclic and dynamic loadings show the performance of the approach. The macro-element approach of SSI phenomena for NPP buildings seems to be a promising way for the seismic Safety Assessment studies when high seismic solicitations or high slenderness ratio have to be taken into account, with induced uplift and soil plastic hinging. Moreover, due to the low computational costs, this approach is suitable for performing parametrical studies by taking into account the stochastic nature of the input dynamic solicitation.

Keywords: Soil-structure interaction; plasticity; uplift; macro-element; foundation; dynamic

Session – Methodologies and Frameworks

Nonlinear Soil-Structure Interaction Analysis: A Comparison between 3D Finite Element Method and Macro-Element Modelling

Fan Wang (CEA) and Jean-Mathieu Rambach (IRSN)

Recent observations of very strong earthquakes affecting nuclear power plants such as the NCOE earthquake (Japan) in 2007 and the need to assess the safety margin of nuclear installations for beyond design seismic events have made it increasingly necessary to consider nonlinear effect in soil-structure interaction analysis.

In recent years, non linear macro-element modelling has been developed by different authors as a convenient tool to take into account soil nonlinearities for structures on shallow foundations. In this simplified modelling, the foundation motion is entirely governed by a set of generalised forces and displacements defined at the centre of the foundation. The rigid foundation and the soil in the influence zone are combined into a single macro-element. One of these macro-element formulations has just been implemented in CAST3M, a finite element code developed in CEA. This element is capable to simulate the 3D nonlinear behaviour of circular and rectangular shallow foundations under static and dynamic loadings.

On the other hand, with the increasing computing and storage capacity of nowadays computers, it becomes possible to address 3D non linearity problems in SSI analysis with local finite elements modelling. A procedure has been implemented in CAST3M to perform this kind of computations. It is based on the so called "direct method" in which the structure and the near field soil are modelled with finite elements whereas the far field soil by absorbing boundaries. The resolution of the problem is carried out by time domain integration. This makes it possible to deal with all kinds of material and geometrical nonlinearities.

After a brief review of their implementations, this paper will present a comparative study of the two approaches in a number of hypothetical situations. Two kinds of nonlinear behaviours will be addressed. The first one is the soil yielding in the influence zone in the vicinity of the foundation and the second one is the gap formation between the footing and the underlying soil (partial uplift). By comparing the simulation results of the two approaches under seismic loadings, we will evaluate their practical performances and find out their relative strengths and limitations.

Deterministic and Probabilistic Seismic Soil Structure Interaction Analysis of the Mühleberg Nuclear Power Plant SUSAN Building

David K. Nakaki, Philip S. Hashimoto (Simpson Gumpertz & Heger, Inc.), James J. Johnson (James J. Johnson & Associates), Yahya Bayraktarli and Olivier Zuchuat (BKW FMB Energie AG)

Deterministic and probabilistic seismic soil structure interaction (SSI) analysis was performed for the Mühleberg Nuclear Power Plant SUSAN Building in support of the seismic probabilistic risk assessment of the plant. An efficient hybrid method, employing computer programs SASSI2000 and CLASSI was used in this analysis. The method takes advantage of the capability of SASSI2000 to analyze embedded structures with irregular geometry and the computational efficiency of CLASSI to rapidly perform the SSI response analysis of large structure models. A detailed fixed base finite element model of the building was first developed to calculate natural frequencies and mode shapes. The structure embedment was modeled using SASSI2000 in which the layered site was represented by the median centered earthquake strain compatible soil profile. Impedance functions and scattering vectors were calculated by imposing rigid body constraints to the embedded foundation. The fixed base structure dynamic properties and the foundation impedances and scattering functions were input to CLASSI to perform the response analysis. Median centered deterministic SSI analysis was first performed in which the input ground motion consisted of a single, three component set of acceleration time histories compatible with the site surface uniform hazard spectrum. In-structure response spectra (ISRS) were calculated at selected locations in the building. The subsequent probabilistic analysis was performed following the Latin Hypercube Simulation (LHS) approach documented in NUREG/CR-2015. Variables in the LHS included the earthquake ground acceleration time histories, structure stiffness and damping, and soil stiffness and damping. Thirty response simulations were performed using CLASSI in which the variable values were randomly selected. The use of CLASSI has the advantage that the response analysis simulations can be executed in a fraction of the time that would be required with SASSI2000 alone. For each simulation, ISRS were calculated. Probability distributions, described by the median and 84th percentile response spectra, were calculated from the thirty simulations. The deterministic median-centered ISRS and probabilistic ISRS were compared. This demonstrated consistency between the two methods and also highlighted the result in which sharp spectral acceleration peaks in the deterministic ISRS were reduced in the probabilistic analysis.

Session – Case Studies / Analysis in Frequency Domain

Seismic Motion Incoherency Effects for Nuclear Islands on Soft Soil Site Conditions

Dan M. Ghiocel (GP Technologies, Inc.), Steve Short and Greg Hardy (Simpson, Gumpertz and Heger)

The paper presents results obtained from a sequence of parametric SSI studies using the AP1000-based stick SSI model that was also employed in recent EPRI studies [1]. The paper focuses on the effects of incoherency for surface and embedded foundations.

The investigated case studies were based on the surface AP1000-based stick model used in the EPRI studies with two different foundation mat sizes, 150ft x 150ft and 160ft x 255ft, respectively. The AP1000-based stick model used in EPRI studies was modified by changing the mat size. Both surface and embedded models will be used. The embedded foundation walls were modeled by elastic shell elements. For seismic input motion we considered the RG 1.60 input applied in conjunction with the 2007 Abrahamson soil coherency model. Soil layering was assumed to be uniform with Vs of 1000 fps. In addition to the motion incoherency effects we also looked at the wave passage effects. The incoherent versus coherent SSI results are compared in terms of maximum accelerations, ISRS and shear forces and bending moments in the structural stick elements.

Using the Luco-Wong parametric coherency model, we also study the effects of motion the incoherency directionality. Anisotropic and isotropic motion incoherency results obtained for the AP1000 stick model are compared. Comparative results are ISRS and strutural forces and moments.

For soil sites, the motion incoherency effects manifest at much lower frequencies, well below 10Hz, where governing structural vibration modes exist. For structures with significant mass eccentricities, motion incoherency effects could amplify the torsional SSI responses, as shown herein for the AP1000-based stick model on a soil site, in one horizontal direction. Presented results indicate that the effects of motion incoherency are significant for soil sites.

More detailed conclusions and recommendations will be included in the paper manuscript.

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Session – Case Studies / Analysis in Frequency Domain

Seismic SSI Effects for APWR Reactor Building Complex

Ghiocel Dan Mircea (GP Technologies, Inc.), Luben Todorovski (URS Washington Division) and Hiroyuki Fuyama (Mitsubishi Heavy Industries)

The seismic responses obtained from soil structure interaction (SSI) analyses form the basis for earthquake resistant design of nuclear power plants. The numerical models used for SSI analyses have to be able to capture the overall dynamic behavior of the building but are not sufficiently refined to capture local stresses distributions or to provide detailed representation of all subsystems and components that are required for a reliable design. The results of the SSI analyses serve as basis for development of seismic design parameters that define the seismic demands applied to more detailed numerical models. The seismic design of structural members of category I and II buildings is based on seismic loads usually defined in terms of quasi-static accelerations. In structure response spectra (ISRS) are used to define the seismic demands for the design of seismic category I and II subsystems, components and equipment. The reliability of the seismic design depends on the methodologies used for the SSI analyses and development of seismic demands as well the actual dynamic properties of the structure and seismological, geological characteristics of the site.

The objective of this paper is based on case study to illustrate how the selection of methodology for SSI analysis and development of seismic demands appropriate can affect the design. The case study is based on the SSI analyses of the US APWR R/B Complex founded on a rock site and partially embedded in 40 ft of backfill soil. The APWR R/B complex SSI model is a multiple stick model with a continuos foundation described by shell elements. The seismic response of the building is investigated when subjected to two types of input ground motions: (1) with frequency content and PGA of 0.3 g similar to the US NRC RG 1.60 [1] Design Spectra; and (2) with high frequency content and high PGA that is characteristic for rock sites in Eastern US. The study addresses the effects of the ground motion incoherency on the structural response at high frequencies using the stochastic simulation approach implemented in the ACS SASSI code that has been validated by EPRI [2].

The SSI analysis results indicates that the seismic structural design based on the response obtained considering Reg Guide type of input ground motion envelope the seismic demands resulting from the high frequency input motion with higher PGA than 0.3g. The study shows that the stress results from the SSI analysis help capture the phasing of the higher modes of vibration and provide better basis for the development of seismic loads than the maximum acceleration results. The study also shows that the input ground motion incoherency can significantly affect the ISRS at high frequency. The use of appropriate methodologies for SSI analyses and development of seismic demands from SSI analyses lead to more realistic design of subsystem components and equipment for sites characterized by input motion with high frequency content.

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Session – Case Studies / Analysis in Frequency Domain

Effects of Surface Geometry in SSI-Analyses

Alejandro P. Asfura

One of the limitations of the commonly used soil-structure interaction codes is the assumption that the soil profile consists of infinite horizontal layers and that the soil surface consists of a perfectly horizontal plane. Reality is that neither the soil profile nor the soil surface is infinitely horizontal.

This paper studies a case where the soil surface has a discontinuity near the structure. This discontinuity could consist of a slope or a vertical cut in the soil profile. The goal of this study is to determine how far from the structure this discontinuity needs to be so the assumption of infinitely horizontal surface is still valid.

A series of two-dimensional soil-structure interaction analyses are performed for a case of a structure near a slope. In these analyses, the distance from the structure to the slope, the soil properties, and the properties of the structure are varied to determine the minimum distance for which the assumption of infinitely horizontal surface is valid.

Two series of two-dimensional soil-structure interaction analyses are performed: one in the frequency domain with program SASSI considering that the soil surface is infinitely horizontal; and one in the time domain with program QUAD4 considering the actual geometry of the soil surface. The results from both series are compared to study the effects of the surface geometry in the structure response, and to determine the minimum distance, as function of the soil and structure characteristics, for which the assumption of infinitely horizontal soil surface is valid.

Session – Case Studies / Analysis in Frequency Domain

Soil Structure Interaction (SSI) Analysis of the Kashiwazaki-Kariwa Unit 7 Reactor Building under the NCOE excitation in the Context of the IAEA KARISMA Benchmark

J. Moore (Basler & Hofmann AG)

The International Atomic Energy Association (IAEA) launched a prediction contest benchmark entitled KARISMA in 2008. This benchmark was created in response to the Niigataken-Chuetsu-Oki Earthquake (NCOE), which occurred on July 16, 2007 off the coast of Japan. The earthquake affected the Tokyo Kashiwazaki-Kariwa Nuclear Power Station (NPS) located just 16 km away from the epicenter. As participants within this benchmark, the team of ENSI (Swiss Federal Nuclear Safety Inspectorate) and Basler & Hofmann Consulting Engineers has developed a soil structure interaction (SSI) analysis model using the program ACS SASSI to best predict the seismic response of the Unit 7 reactor building under the NCOE excitation. The development of this model, as well as the resulting modal analysis and frequency domain analysis predictions, are presented in this paper.

Session – Case Studies / Analysis in Frequency Domain

EPRI AP1000 Model Studies on Seismic Incoherent SSI Effects for A Hypothetical Site Condition That Includes 40 ft Backfill Soil Over A Stiff Rock Formation

Dan Mircea Ghiocel (GP Technologies, Inc.), Dali Li, Nicholas T. Brown, Jennifer Jie Zhang, and Leonardo Tunon-Sanjur (Westinghouse)

The paper shows the effects of seismic free-field motion incoherency on the soil-structure interaction (SSI) response using the EPRI AP1000 nuclear island (NI) stick model [1] founded on a rock site with 40 ft of backfill soil above the rock grade. For this study, the EPRI AP1000 stick model basemat was modified reflect the real foundation size of the AP1000 NI.

Two case studies are considered using 3D SSI structural stick models with rigid basemats:

1) Isolated EPRI AP1000 NI and Aux Bldg stick models and

2) Coupled EPRI AP1000 NI-Aux Bldg stick model.

Coherent vs. incoherent SSI analyses are performed for the isolated and coupled structures. For the isolated EPRI AP1000 stick we considered both the surface and the embedded foundation cases. The seismic input is defined by the HRHF ground surface response spectrum that was used in the EPRI studies [1] anchored to a ZPGA of 0.30g. The 2007 Abrahamson coherency model for hard-rock site wa considered.

Comparative results show the effects of motion incoherency on i) In-Structure Response Spectra (ISRS), ii) ZPAs, iii) structural forces and moments in the sticks, iii) structural relative displacements with respect to the free-field control motion and between the two neighbour foundations, and iv) seismic pressure distributions on foundation walls and basemat.

Incoherent SSI analyses are performed using stochastic simulation approach that was validated by EPRI [1]. For SSI analyses we employed the ACS SASSI NQA Version 2.3.0 software that includes a powerful ANSYS interface for computing structural forces and soil pressures on foundation walls using refined equivalent-static linear/nonlinear FE models. For seismic pressure calculations we included both the effects of the soil nonlinear hysteretic behavior and the soil-foundation separation. Various SSI result comparisons for isolated and coupled building models, coherent and incoherent inputs, nonlinear and linear soil models, with and without soil separation, will be shown. Comparisons between surface and embedded EPRI AP1000 stick models will be also discussed. Finally, insightful conclusions will be provided.

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Session – Case Studies / Analysis in Frequency Domain

Seismic Motion Incoherency Effects for CANDU 6 Reactor Building Structure

Dan M. Ghiocel (GP Technologies, Inc.), Sudip Adhikari, George Stoyanov, and Tarek Aziz (AECL Ltd.)

The paper presents results obtained from a sequence of SSI studies for the CANDU 6 Reactor Building (RB) founded on a stiff soil deposit and a hard-rock formation. The analysis were performed using the design-bases RB stick model and an enhanced high-frequency (HF) RB model for which the containment is modeled more realistically by shell elements. Seismic inputs were defined by site-specific UHRS that have a significant HF content.

The seismic motion incoherency effects were studied using SSI methodologies validated by EPRI [1]. The 2007 Abrahamson plane-wave coherency model was considered. The effect of wave passage is also investigated. The paper addresses the effects of incoherency for both surface and partially embedded RB foundation.

The coherent and incoherent SSI results were compared in terms of maximum accelerations, acceleration transfer function (ATF) and in-structure response spectra (ISRS) at different locations on the containment shell (CS) and internal structure (IS).

The ATF and ISRS results indicated significant reductions in high-frequency range due to incoherency effects. The ISRS amplitude reductions are larger for the CS and at the center of the IS floors and much less reduced at the IS floor corners. The effects of embedment are significant in lower frequency range, especially for the soil stiff deposit for which the reduction of the ground motion at foundation level is large, falling below the 60% amplitude reduction limit required by CSA standard.

It should be noted that the type of modeling of CS influences the CS-IS coupling at the frequency associated to the global torsion of the IS. If shell elements are used instead of beams an additional spectral peak is noted for the ISRS computed for CS.

More detailed conclusions and recommendations will be included in the paper manuscript.

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Session – Case Studies / Analysis in Frequency Domain

Recent Experiences with Soil-Structure Interaction Analyses for Nuclear Facilities

Tarek Aziz, Richard Chen, Wei Liu, Sudip Adhikari, George Stoyanov, and Qinghua Huang (Atomic Energy of Canada Limited)

The importance of soil-structure interaction (SSI) analysis has been well-recognized in nuclear facilities design since the early 1970s. This type of analysis has evolved from its early days and has become an indispensable tool in producing realistic designs and satisfying ever evolving regulatory requirements. In recent years there has been an increased interest in this type of analysis with respect to safety issues which continue to be of the highest importance in nuclear facilities design. The most crucial of these issues are the significant increase of the seismic input in high frequency range and seismic incoherency effects on structural behaviour.

Previously, the effect of embedment on structural behaviour was to increase resonant frequencies and usually a decreased structural response when compared with the response of the same structure founded on the surface of the soil. It is for this reason that recent standards (e.g. ASCE-4-98) allows the effect of embedment to be neglected in obtaining the impedance functions for shallow embedment since it was considered a conservative assumption to do so. However, current seismic hazard assessments express hazard in terms of a Uniform Hazard Spectrum (UHS) and it is found that high frequency content is present in the UHS for nuclear facilities in Central and Eastern North America. Therefore, it may not be conservative to neglect embedment in seismic analysis with high frequency motions since the potential increase of frequencies may lead to an increase of the seismic response.

AECL has gained valuable experience in analyzing CANDU nuclear power plants and facilities for different foundation and site conditions.

SSI analyses for rock sites, soil with underlying rock sites have been performed for CANDU reactor building structures. Also SSI analysis for very deep alluvial site has been performed. In the course of this work, studies for the following effects have been performed: incoherency effect, seismic wave passage effect, embedment effect, effect of variations of interaction boundary definition for embedded models among several others.

SSI analysis work has been verified and compared against fixed base and impedance method results which were obtained by using several structural analysis programs. For site specific geotechnical conditions "soil" column analyses have also been performed to determine suitable input motions for use in SSI. The paper presents a summary of the most important results and findings from recent SSI work on a number of projects performed by AECL.

Session – Case Studies / Analysis in Time Domain

Keynote Paper

On Seismic Soil Structure Interaction Simulations for Nuclear Power Plants

Boris Jeremić (Department of Civil and Environmental Engineering, University of California)

Seismic Soil Structure Interaction (SSI) of Nuclear Power Plants (NPP) has attracted significant attentions for a long time. This is quite understandable having in mind the significant seismic safety issues related to NPPs, their size and the complexity of NPP soil-structure system (NPPSSS).

This talk will focus on three important aspects of SSI simulations for NPPSSSs:

- Consistent following of input seismic energy and a number of energy dissipation mechanisms within NPPSSSs,
- Review of numerical techniques currently used to simulate dynamics of SSI for NPPSSS (in both time and frequency domain)
- Influence of uncertainty of SSI simulations, particularly related to variability and uncertainty of soil/rock within NPPSSSSs.

The SSI of NPPSSSs is controlled by the interaction of dynamic characteristics of soil/rock, foundation and the structural system with dynamic characteristics of seismic ground motions. Numerical modeling and simulation of spatial distribution of seismic energy in time can elucidate SSI behavior and help improve safety and economy of NPPSSSs. Different numerical techniques, that bring different strengths to SSI simulations, will be critically reviewed with particular emphasis on energy propagation simulations. Seismic energy propagation simulations can benefit the design and licensing process by exposing regions where and when energy dissipation occurs, signifying damage or unacceptable performance. Modeling of uncertainties associated with earthquake source characteristics and propagation through uncertain soil/rock adds to the complexity, however it also allows for proper probabilistic presentation of results. Modeling of uncertainty also allows for probabilistic based decision process which improves safety and economy of NPPSSSs.

A number of numerical examples will be used to illustrate above topics as well as to propose a novel, direct time domain approach to modelling and simulation of soil-structure interaction for Nuclear Power Plant Soil Structure Systems.

Session – Case Studies / Analysis in Time Domain

Recent Advances in Non-Linear Soil-Structure Interaction Analysis Using LS-DYNA

Michael Willford, Richard Sturt, Yuli Huang, Ibrahim Almufti, and Xiaonian Duan (Arup)

LS-DYNA is a versatile non-linear dynamic analysis platform with a large library of material models and element formulations suitable for computationally intensive time-domain multi-physics simulation. The authors have been involved in the development of new features in LS-DYNA for non-linear static and dynamic soil-structure interaction analysis, and have used the software for the design of complex infrastructure projects internationally for over 15 years.

The paper will first describe features in the software to model:

- non linear behavior of soil and backfill material, including strain rate effects, pore water pressure generation and liquefaction
- 3D basement construction sequence analysis, resulting ground movements and soil stress state changes
- non-linear behavior of concrete
- non-linear behavior of piled foundations
- partial separation of foundation and soil
- explicit incorporation of seismic isolation systems
- incoherency of earthquake motions
- boundary considerations

The paper will then illustrate the application of the software to a number of projects in which seismic soil-structure interaction played a crucial part in the design. These include examples of:

- Offshore platforms
- Bridges
- Liquefied Natural Gas tanks
- Construction of large excavations adjacent to heavy buildings

The paper will conclude with an overview of the advantages of the non-linear time domain technique to soil-structure interaction problems in the Nuclear Power industry.

Session – Case Studies / Analysis in Time Domain

Transient Finite-Element Soil-Structure Interaction Analysis of Nuclear Power Plants

Ushnish Basu (Livermore Software Technology Corp) and Anil K. Chopra (University of California)

Two outstanding issues make it challenging to carry out soil-structure interaction analyses of nuclear power plants: (i) modeling of the unbounded foundation domain to allow radiation damping, and (ii) incorporating the free-field ground motion. Additionally, any method of analysis needs to allow realistic modeling of structure, including concrete cracking, non-linear soil or backfill material, embedment of the structure and separation of foundation and soil. Current methods of analysis typically apply a deconvoluted ground motion at depth and model the unbounded domain using a dashpot boundary, while using equivalent linear soil models in the frequency domain or non-linear models in the time domain. Analysts are compelled to use these approximate methods in the absence of a more accurate and efficient approach.

This paper presents a rational and efficient method for soil-structure interaction analysis that produces accurate results using a small bounded domain for the foundation and only the free-field ground motion at the soil-structure interface. This approach uses perfectly matched layers — a novel absorbing layer model that absorbs all waves nearly perfectly — to model the unbounded domain. Furthermore, it uses the effective seismic input method to directly incorporate the free-field ground motion into the model without any deconvolution. This method is the time-domain equivalent of the frequency-domain substructure method and is mathematically equivalent to propagating the earthquake from the fault to the site.

This approach is entirely finite-element based, and as such can be used with realistic finite-element models for the structure. The method has been implemented and validated in LS-DYNA, a well-established general-purpose finite-element software that has inter alia (i) a wide range of material models for concrete and geomaterials, (ii) robust and efficient capabilities for modeling contact and impact between different parts of the structure. This gives analysts a ready tool for carrying out realistic seismic analyses of nuclear power plants using a detailed model of the structure while incorporating the soil-structure interaction effects in a rational, inexpensive and accurate manner.

Session – Case Studies / Analysis in Time Domain

Soil Structure Interaction Studies of a Safety Related Nuclear Facility

G. Padmanabhan, C.Sundaramurthy, and C.Sivathanupillai (IGCAR)

Key words: Shear wave velocity, Low strain Shear modulus, Seismic Cross hole survey, SSI analysis

Inter dependent response relation between a structures and its supporting soil popularly known as Soil Structure Interaction is an important aspect with respect to Nuclear Power Plant Structures and facilities. Proper evaluation of the nature of subsoil is an important step in SSI analysis. Determination of Shear wave velocity and Low strain Shear Modulus are the important parameters required for carrying out Soil Structure Interaction Studies. Site investigations are required right from the selection of site, detailed engineering stage and during confirmatory stage to evaluate these parameters. This paper addresses Seismic and Geotechnical characterization carried out at a nuclear facility site located along East Coast of Peninsular India. Soil structure interaction study was carried out for a facility located at this site using these parameters according to ASCE-4-98 and the results are discussed.

Seismic refraction survey and Seismic cross hole survey were carried out to evaluate the design parameters required for Soil Structure Interaction Studies. Relationships were developed between shear wave velocity and compression wave velocities based on these investigations. Average shear wave velocity of the top 30m soil is evaluated and the fundamental period of site is estimated. A range analysis was performed to account the uncertainties in SSI analysis. The requirement of adequate site investigation to evaluate the mean and standard deviation of low strain shear modulus is also addressed.

A safety related structure which is irregular with stiffness discontinuities were selected for carrying out SSI analysis as it is not supported by rock or rock-like soil foundation material. The type of foundation fixity required for the analysis was carried out from the shear wave velocity obtained. SSI analysis was carried out using impedance method as per ASCE 4-98 for the Site specific spectra and that suggested by TECDOC 1347. The results are discussed and compared. The response of the structure for a fixed base analysis and SSI analysis are obtained and discussed.

Session – Case Studies / Analysis in Time Domain

Development of an Evaluation Response Spectrum for the Seismic Risk Assessment of a Nuclear Waste Repository in Korea

Min Kyu Kim, In-Kil Choi (KAERI)

An evaluation response spectrum for seismic risk assessment of nuclear waste repository in Korea was developed in this study. For the development of evaluation response spectrum, a seismic hazard analysis, evaluation of uniform hazard spectrum, generation of artificial time history acceleration and site response analysis were performed. For the performing a seismic hazard analysis, a seismic source model and input parameters were selected. The Gutenberg Richter a-value and b-value, moment magnitude and focal depth were decided. Attenuation equation was decided as midcontinent of Toro. Using the seismic source, input parameters and attenuation equation, a seismic hazard curve for base rock site was developed through the seismic hazard analysis. The seismic hazard curve should be transformed for underground structure. A uniform hazard spectrum was generated by using the seismic hazard curve for generation of artificial acceleration time history. The 30 artificial seismic acceleration time histories were generated based on the uniform hazard spectrum by using P-CARES program. A seismic response analysis was performed of 30 artificial acceleration time histories for target nuclear waste repository site for the development of evaluation response spectrum. Finally, an evaluation response spectrum for seismic risk assessment of nuclear waste repository was proposed.

Key words: evaluation response spectrum, seismic risk assessment, nuclear waste repository, seismic hazard analysis, uniform hazard spectrum, seismic response analysis

Session – Case Studies / Analysis in Time Domain

Recent Advances in Seismic Soil-Structure Interaction Analysis of Nuclear Power Plants

Mansour Tabatabaie, (SC Solutions, Inc.)

Three-dimensional seismic soil-structure interaction (SSI) analysis of nuclear power plants (NPPs) is often performed in the frequency domain using programs such as SASSI. This enables the analyst to properly a) address the effects of wave propagation in an unbounded soil media, b) incorporate strain-compatible soil shear modulus and damping properties, and c) specify input motion in the free field using the de-convolution method and/or spatially variable incoherent ground motions. However, the size of the SSI system that could potentially be analyzed by SASSI has been limited to coarse finite element models of structures. Furthermore, for structural systems exhibiting nonlinearities at the soil/structure interface (such as potential base sliding and/or uplift and sidewall/back soil separation) as well as within the structure (such as component isolation, etc.), the frequency-domain procedure is not applicable as it is limited to linear systems. While these problems require solution in the time domain using the direct integration method, the available software is limited in its capability to model the dynamic SSI effects.

This paper begins with a discussion of the recent advancements in the use of SASSI to analyze large and detailed structural systems with deep embedment. It will address several SSI analysis and design issues, such as stick versus detailed structural modeling, basemat and floor/wall flexibility, backfill soil modeling, cracked concrete modeling, foundation mesh refinement, dynamic soil pressures and structure-soil-structure interaction (SSSI) effects.

A methodology for performing SSI analysis in the time domain is discussed next. This methodology is based on the distributed parameter foundation impedance (DPFI) model, which allows the structure to be partitioned from the total SSI system and analyzed in the time domain while the foundation soil is modeled using the frequency-domain procedure. To evaluate the effectiveness of this method for linear systems, the seismic response of a typical NPP model calculated in the time domain using DPFI (derived from SASSI) is compared to the seismic response obtained by a one-step SASSI analysis of the total SSI system (target solution). The DPFI model is then expanded to incorporate nonlinearities at the soil/structure interface by introducing nonlinear shear and normal springs arranged in series between the DPFI and structure model. This combination of linear far-field impedance (DPFI) and nonlinear near-field soil springs allows the foundation sliding and/or uplift to be analyzed in the time domain while maintaining the frequency-dependent stiffness and radiation damping of the far-field foundation impedance. The effectiveness of this procedure is evaluated by comparing the dynamic response of a typical NPP basemat (supported at the ground surface and subjected to base sliding) calculated in the time domain using DPFI/nonlinear soil springs and continuum soil model (target solution).

Session – Case Studies / Analysis in Time Domain and Some Special Topics

Keynote Paper

Non Linear Soil Structure Interaction: Impact on the Seismic Response Of Structures

Alain Pecker (Géodynamique et Structure)

New developments in structural earthquake engineering are definitely directed towards performance based design approaches. In geotechnical earthquake engineering performance based design has, until recently, received little attention. Obviously the main reason is that the essential prerequisite to performance based design is a reliable estimation of the induced displacements. Any geotechnical engineer is aware of the difficulties in predicting foundation settlements because of the important variability of soil properties, even in a presumably homogeneous medium, and of the highly non linear behaviour of soils. These difficulties still hold for earthquake loading but they are aggravated by the strong interaction that exists between the inertia forces developed in the superstructure and the response of the foundation; this phenomenon is known as soil structure interaction (SSI). Since the early seventies, SSI has received a great deal of attention and seismic analyses taking into account SSI have become standard practice in earthquake engineering, at least for important structures. However SSI is restricted to linear phenomena and is used only to evaluate the structural inertia forces; it cannot give an estimate of residual displacements when the foundation starts to yield.

Several possibilities are offered to the designer to calculate the foundations displacements induced by severe earthquake loading. For instance several authors have proposed to retrieve the forces acting on the foundation, calculated in a preliminary analysis accounting for SSI effects, and to carry out a Newmark type of analysis assuming a predetermined failure mechanism in the soil; obviously, although convincing results were obtained, the method suffers from several drawbacks, the most obvious one being the lack of consideration for the changes in the forces as the foundation yields. The second alternative would be to build a global finite element model in which the structure, its foundation and the supporting soil are modelled; this approach is very demanding in terms of man hours and computer time, highly dependent on the choice of the soil constitutive model and not very amenable to parametric studies required at a design stage. The method is more suited for final verifications than preliminary design. The third, very attractive, alternative belongs to the class of dynamic macro element models that have emerged during the last decade since the pioneering work of Paolucci (1997), Pedretti (1998), Cremer-Pecker-Davenne (2001, 2002). It is build up on the original work by Cremer et al, has been extended to 3D circular foundations, is applicable to cohesive and cohesionless soils and has been considerably simplified, which makes it much more efficient from a numerical standpoint (Chatzigogos-Pecker-Salençon 2009a, 2009b; Chatzigogos-Figini-Pecker-Salençon 2010).

The objective of such a tool is to model the effects on the dynamic response of the superstructure of the soil-structure interaction non-linearities that arise at the foundation level. The model couples the two separate sources of non-linearity at the foundation level: the first one is due to the irreversible elastoplastic soil response accounting for the material non-linearity in the system; the second source of nonlinearity, of geometric nature, is due to the uplift that may arise at the soil-foundation interface. The model has been qualitatively validated against results from centrifuge tests conducted on a footing subjected to quasi-static monotonic and cyclic loading.

The efficiency of the model will be illustrated by performing incremental dynamic analyses (IDA) of a simple structural system with consideration of non linear soil structure interaction. Three base conditions are examined, namely fixed base, linear foundation and non-linear foundation including uplift and soil plasticity. IDA curves are produced for a variety of intensity and damage parameters describing both the maximum and the residual response of the system. The results highlight the beneficial role of foundation non linearities in decreasing the ductility demand in the superstructure.

Session – Case Studies / Analysis in Time Domain and Some Special Topics

Soil-Structure Interaction and Wave Passage Effects in Nonlinear Soil

M. D. Trifunac (Dept. of Civil Eng., Univ. Southern California)

Two-dimensional model of a building supported by flexible foundation embedded in nonlinear soil is analyzed. The model is excited by half-sine SH wave pulse, which travels toward the foundation with arbitrary angle of incidence. The results show that the spatial distribution of permanent, nonlinear strain in the soil depends upon the incident angle, and the amplitude and the duration of the pulse. If the wave has large amplitude and short duration, nonlinear zone in the soil appears immediately after the reflection from the half-space and is located close to the free surface. This results from interference of the reflected pulse from the free surface and the incoming part of the pulse that still has not reached the free surface. When the wave reaches the foundation, it is divided into two parts: (1) the first part is reflected, and (2) the second part enters the foundation. Further there is separation of this second part at the foundation-building contact. One part is reflected back, and one part enters the building. This process continues until all of the energy in the building is released back into the soil. The work needed for the development of nonlinear strains in the soil can absorb considerable part of the input wave energy, and thus smaller energy is available for exciting the building. However, the nonlinear zones in the soil, which are created in this process, are not symmetric with respect to a vertical axis through the foundation, and this asymmetry can lead to amplification of torsional and rocking responses of the foundation-structure system. These asymmetries may remain at the site for many years and may affect the soil-foundation-structure response during many subsequent earthquakes.

Non-Linear SSI Calculations: Methods to Determine Raft Uplift

Pauline Billion, Frédéric Allain, Georges Devesa, Nicolas Humbert and Ilie Petre-Lazar (EDF, Electricité de France)

In the last years, projects taking into account the SSI have emerged in the nuclear engineering department of EDF. We focus in this paper on uplifting calculations.

Before those calculations, a synthesis of all the methods used in EDF has been made. Both linear and non-linear uplifting calculations methods exist.

The uplifting phenomenon is not a straightforward one to observe as it occurs promptly and the displacements and rotation values involved are small. Hence the goal of the uplifting calculations is to obtain orders of magnitude of the phenomenon, using simplified methods.

There are two methods based on a transitory modal analysis. Both are linked to a moment-rotation relation but its integration varies from one method to another. For a first linear method, the M-θ relation is integrated in the post-processing after the modal analysis. This energy equivalence method is based on the fact that a non-linear system response (with uplifting) is approximated assuming that the energy transmitted to the system is equal to the one calculated from a linear model. A 3D-model is therefore considered as a plane model. After a linear calculation, a maximum moment at the centre of the raft is determined and a rotation value is therefore deduced. This method tends to overestimate the uplifted area percentage. This method was set up in EDF in the 1980s.

A second method is a non-linear one that uses the M-θ relation. It is directly integrated to the calculation via an operator, where the non-linear relation M-θ is introduced step by step.

A direct non-linear transitory method can also be used. In that case, a second layer of non-linear springs is added under the raft. The contact is broken as soon as the springs are not compressed anymore. The gravity is imposed to the structure and to the soil springs before imposing the seismic loadings and calculating the uplifted area. This method is the one currently used in EDF.

Comparisons were made for different nuclear buildings and different time histories. It concluded that on a medium homogeneous soil, results can vary from 0 to 51% of uplifted area under a 0.25g earthquake and from 25 to 70% under a 0.5g one, results do not diverge from one another. It has yet been shown that the accelerogram sets used can greatly influence the uplifted area results.

A previous study was carried out in order to compare a non-linear transitory analysis and the energy equivalence method. It concluded that differences are not significant.

We conclude that direct methods represent more realistic methods compared to the other ones. Some drawbacks can nevertheless be highlighted: great calculations time, difficulties to estimate the area depending on the raft shape. The energy equivalence method has the advantage of not being time-consuming but overestimated values of uplifted area are found.

Impedance Calculations for Foundations on Soil Reinforced with Concrete Inclusions

Didrik Vandeputte, Pauline Billion, Alexis Courtois, and Pierre Labbe (Edf, Electricité De France)

Context

EDF is responsible for the dismantling of 9 nuclear sites in France. Dismantling will produce 300 tons of long-life radioactive waste intended for deep underground storage. In the meantime EDF will construct an interim storage facility.

The soil profile under the location of this facility revealed an important layer of silty clay – 35m to 50m high – as shown on Figure 1. Preliminary calculations predicted up to 25 cm settlements for the building founded on such a soil. In order to reduce the settlements to less than 5cm, the decision was made to undertake a innovative soil reinforcement. The soil improvement is obtained by the combination of a grid of rigid concrete piles, driven trough the compressible soil layer until the rigid stratum, and a granular earth platform situated between the improved ground and the surface structure. About 300 concrete inclusions (ϕ=1m) are planned to be set for this new EDF facility. The influence of these inclusions on Soil Structure Interaction phenomenon has been studied and taken into account for the impedance function calculations of the buildings.

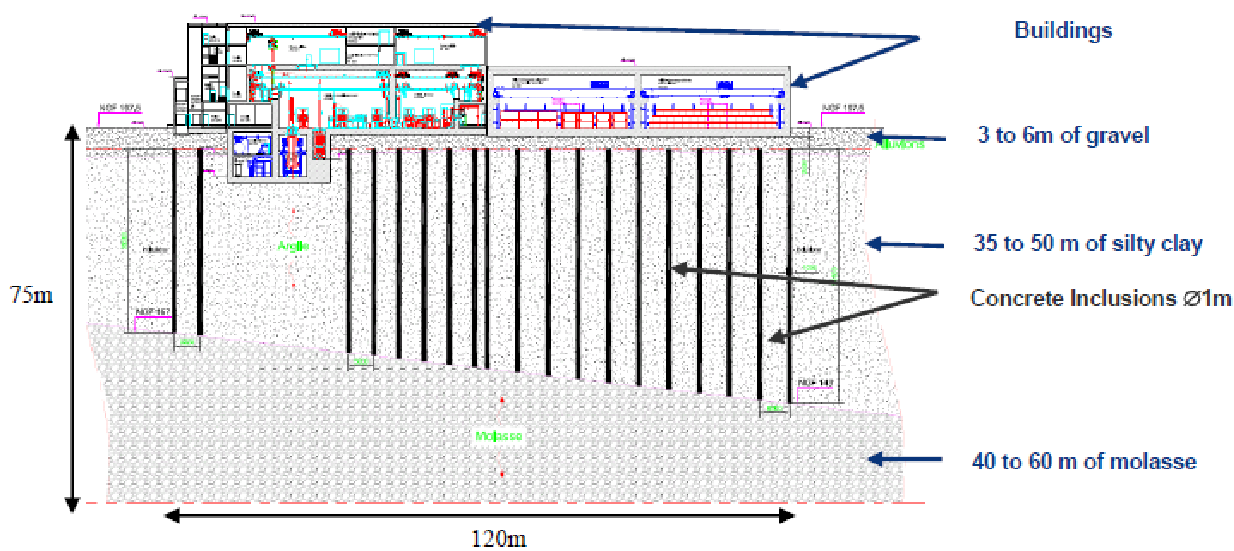

Figure 1 : Soil profile and concrete inclusions under buildings

Impedance calculations

The influence of concrete inclusions inserted into silty clay layer has been experimentally analyzed with Forced Vibration Tests (FVT) performed on 2 identical slabs, dimensions 11m x 11m, one laying on natural soil, the other one built over a system of 9 concrete inclusions.

A 3D-Finite Element model including Boundary Elements, 3D elements for soil and 2D beam elements for inclusions was developed with Code_Aster in order to represent the phenomenon for FVT analysis and impedance calculation.

The Code_Aster results have been compared with experimental data and other SSI codes (SASSI, Miss3D and CONAN) results with good agreement, as shown on Figure 2.

The same kind of model has been applied for all buildings impedance calculations, with appropriate Basic Design margins in order to take into account uncertainties and variability due to soil characteristics and model hypothesis.

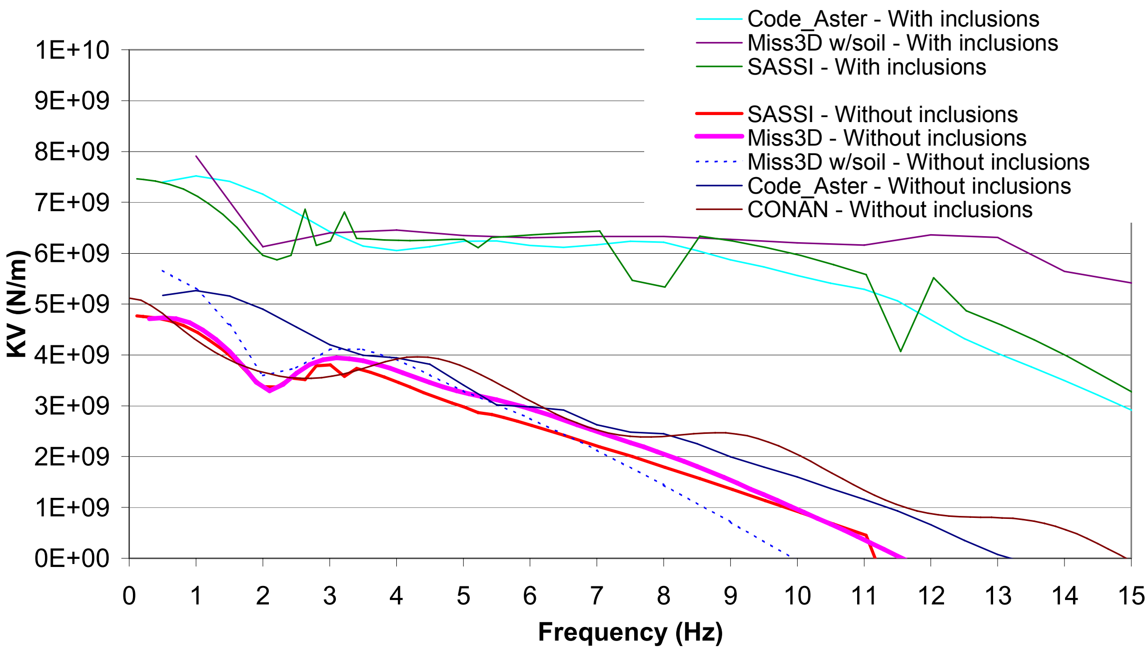

Figure 2 : Vertical Stiffness comparison for test foundation(11m x 11m) with and without inclusions

Conclusion

The impedance functions for the interim storage buildings have been calculated with a Code_Aster 3D-Finite Element model including Boundary Elements, 3D elements for soil and 2D beam elements for inclusions. The results obtained with these model are coherent with the experimental tests and with the results given by other SSI codes like SASSI and Miss3D.

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Session – Case Studies / Analysis in Time Domain and Some Special Topics

Influence of the Soil Nonlinearities on Dynamic Soil-Structure Interaction

A. Gandomzadeh (IRSN), J.F. Semblat, L. Lenti, M.P. Santisi d'Avila (Université Paris-Est) and F. Bonilla (IRSN)

For moderate or strong seismic events, the behavior of the soil (e.g. maximum shear strain) can easily reach its inelastic range. Considering soil-structure interaction, the nonlinear effects may thus change the soil stiffness at the base of the structure and the energy dissipation into the soil.

In this work, a 3D hysteretic model (Masing-Prandtl-Ishlinskii-Iwan model) accounts for the nonlinearity of the soil in order to investigate dynamic soil-structure interaction (DSSI) for significant seismic events. The formulation is made in the framework of the Finite Element Method in the time domain. The constitutive model is fully characterized by the shear modulus degradation curve. This is a key-point since complex constitutive models generally involve numerous mechanical parameters, which are often difficult to determine experimentally.

A parametric study is carried out for different types of structures and various soil profiles to investigate the nonlinear effects. Due to the soil nonlinearity, and depending on the strain level, our numerical results show that part of the incident energy dissipates into the soil before reaching the surface. Consequently, the structural response in terms of acceleration, velocity and displacement at its top decreases. Furthermore, when compared to a structure based on a linear soil, the fundamental frequency of the soil-structure system decreases. The total mass of the structure is also a very important factor strongly influencing the reduction of the fundamental frequency of soil-structure interaction (it is thus very important for large structures such as NPPs structures). The analysis of the energy dissipation process in the soil also illustrates this feature. Finally, the response of the structure is more influenced by the soil nonlinearity when the structure's fundamental frequency is close to the soil natural frequency, the latter depending on the excitation level.

Session – Case Studies / Analysis in Time Domain and Some Special Topics

Analysis of ACR Nuclear Island Seismic SSI: Challenges and Experiences

Nii Allotey, R. Gonzalez, A. Saudy, and M. Elgohary (AECL)

The standard designs of the Advanced CANDU Reactor®, (ACR), and the Enhanced CANDU-6®, (EC6) meet their customer requirements in Canada and worldwide. Both products are designed by Atomic Energy of Canada Limited (AECL) based on the 900 & 700 MWe classes of CANDU reactors, offering nuclear power plants to a broad segment of the power generation market. The seismic design of both nuclear power plants, taking into account the effects of soil structure-interaction (SSI), complies with Canadian standards and with International Atomic Energy Agency safety design standards and guides.

Three-dimensional coarse-mesh finite element model of the nuclear island structures is developed and used in the seismic SSI analyses. The seismic analyses are conducted using ACS SASSI. In performing the seismic SSI analyses of the nuclear island, few challenges were observed. Examples of these challenges include model adequacy for use in subsequent design stages, assessment of interpolated transfer function vis-à-vis un-interpolated transfer functions, longer run-time, smoothing of transfer functions, and distribution of interaction nodes on the foundation boundaries. The seismic SSI of the nuclear island using the coarse-mesh finite element mode highlighted the need to account for in-plane and out-of-plane slab and wall flexibility which would particularly affect the seismic design and qualification of systems and components.

This paper presents the findings of the seismic analyses of the nuclear island structures. A summary of the seismic SSI analysis methodology is presented, along with the observed challenges and gained experiences. The presentation utilizes key parameters of structural seismic response of the nuclear island structures, founded on different design soil conditions, due to the design basis ground motions.

Session – Case Studies / Analysis in Time Domain and Some Special Topics

Kashiwasaki-Kariwa SSI Benchmark Phase I Results

Ayhan Altinyollar, Pierre Sollogoub, Ovidiu Coman, and Antonio Godoy (IAEA)

Niigataken-Chuetsu-Oki earthquake (NCOE), with Mw=6.6, occurred on 16 July 2007 and affected the Kashiwazaki-Kariwa (KK) Nuclear Power Plant (NPP). The distance between KK-NPP and the NCOE epicenter was about 16 Km. The KK-NPP with electrical power of about 8,000 MW is the biggest nuclear power plant in the world. The large amount of observations and data collected on site raised the idea of organizing a benchmark called KARISMA. General objectives of the KARISMA benchmark are the understanding of the soil response, Soil Structure Interaction (SSI) effects during the NCOE and Systems, Structures and Components (SSC) seismic response. KARSIMA activities consist of calibration of different simulation techniques, identification of the main parameters influencing the Soil, Structures and Equipment Components seismic response. KARSIMA benchmark has two main tasks: Task 1 Soil Structure Interaction (including KK Unit 7-Reactor Building (RB)) and Task 2 Equipment response (RHR Piping system, spent fuel pool and a vertical storage water tank). There are about 20 organizations from 14 countries involved.

The first phase of KARISMA Benchmark was completed already. Phases II and III of the benchmark (ongoing) include NCOE simulation and margin assessment. This paper presents synthesis of the benchmark Phase I results.