Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division V

CONTRIBUTION TO THE IAEA SOIL-STRUCTURE INTERACTION KARISMA BENCHMARK

Fan Wang[1], Jean-Mathieu Rambach[2]

[1]CEA, DEN, DM2S, SEMT, EMSI, F-91191 Gif-sur-Yvette, France (fan.wang@cea.fr)
[2]IRSN, DSR/SES/BEGC, IRSN, BP 17, 92262 Fontenay-aux-Roses Cedex, France

ABSTRACT

Following the 2007 NCOE Earthquake in Japan which affected severely the Kashiwazaki-Kariwa nuclear power plant, IAEA launched the KARISMA Benchmark in August 2009 with the objective to find out if current simulation methodologies are able to capture the main features of the seismic response under strong Soil-Structure Interaction (SSI). This paper presents the contribution of the French CEA-IRSN joint team to the the Benchmark.

This work consists of 3D finite element modeling for the structure and the nearby soil and the use of viscous absorbing boundary to represent the far-field soil (lateral sides and bottom). Time domain integration is carried out directly on the coupled soil-structure system. The analysis has given good results compared to the recorded structure response during NCOE earthquake. The same procedure allows us furthermore to perform nonlinear soil-structure interaction analysis under extreme seismic loadings by assuming ground motions 2, 4 and 6 times stronger than the NCOE earthquake. Seismic margin of the reactor building has been quantified.

INTRODUCTION

Following the 16 July 2007 Niigataken-Chuetsu-Oki Earthquake in Japan (NCOE) which affected severely the Kashiwazaki-Kariwa Nuclear Power Plant located just 16 km from the epicenter, and under the initiatives of several organisms among which the CEA France, the International Atomic Energy Agency (IAEA), with the help of TEPCO company, owner of the power plant, launched the KARISMA Benchmark (KAshiwazaki-Kariwa Research Initiative for Seismic Margin Assessment) in August 2009. The power plant is composed of 7 BWR type reactors. The building of the Unit 7 Reactor has been chosen as the subject of the benchmark.

The primary objective is to understand what happened to the soil and structures during the earthquake and to find out if current simulation methodologies used by different countries are able to capture the main features of the seismic response under strong Soil-Structure Interaction (SSI). Another important goal of the benchmark is to evaluate the robustness of the reactor buildings against even stronger earthquakes by quantifying the seismic margin of the structure and the equipment using numerical methods.

A total of approximately 20 teams from about 10 countries participated to the benchmark which was held between 2009 and 2012 in three phases:

- Phase I: Modeling, static and modal analyses, soil column analyses,
- Phase II: Response analyses of the structure and equipment during the NCOE earthquake,
- Phase III: Assessment of the seismic margin by multiplying the seismic level.

The French Commission of Atomic Energy (CEA) and the French Radioprotection and Nuclear Safety Institute (IRSN) formed a joint team in the participation to the “structure part” of KARISMA. This paper presents the contribution of the CEA-IRSN team to the Benchmark.

SSI ANALYSIS USING FINITE ELEMENT METHOD

Soil-structure interaction plays a very important role in this benchmark because the reactor buildings of the power plant are deeply embedded in a relatively soft soil. For SSI analysis, a direct time domain procedure has been implemented in the finite element code CAST3M developed by the CEA (website: http://www-cast3m.cea.fr). The procedure consists of 3D finite element modeling for the structure and the near-field soil and the use of Lysmer and Kuhlemeyer (1969) viscous boundary to represent the far-field soil (lateral sides and bottom) as shown in Figure 1. Time domain integration can be carried out directly on the coupled soil-structure system.

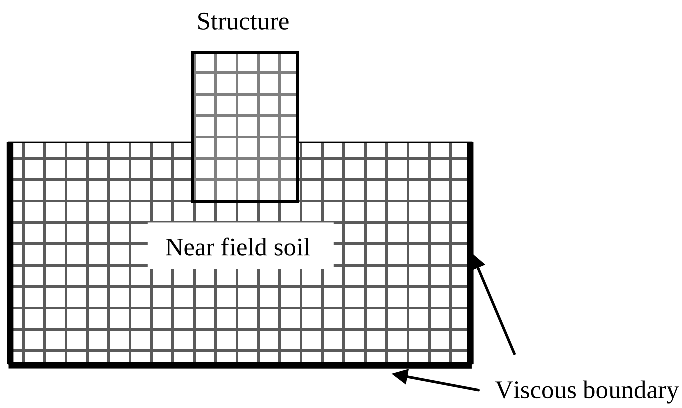


Figure 1. SSI analysis using CAST3M finite element code.

Using the geometric dimensions and material data given by the benchmark organizer, the reactor building is modeled with different types of finite elements. In particular, multilayered shell elements are used for the principal lateral-resistant structural components, i.e. the main shear walls and the Reinforced Concrete Containment Vessel (RCCV). These components are assumed to have nonlinear behaviors under strong seismic loadings. This allows us to perform nonlinear soil-structure interaction analysis under extreme seismic loadings when the structure exhibits nonlinear behaviors such as concrete cracking or reinforcement steel yielding. Soil nonlinearity is also taken into account in the SSI analysis by the usual linear equivalent method.

BENCHMARK PHASE I: STRUCTURE AND SOIL MODELING

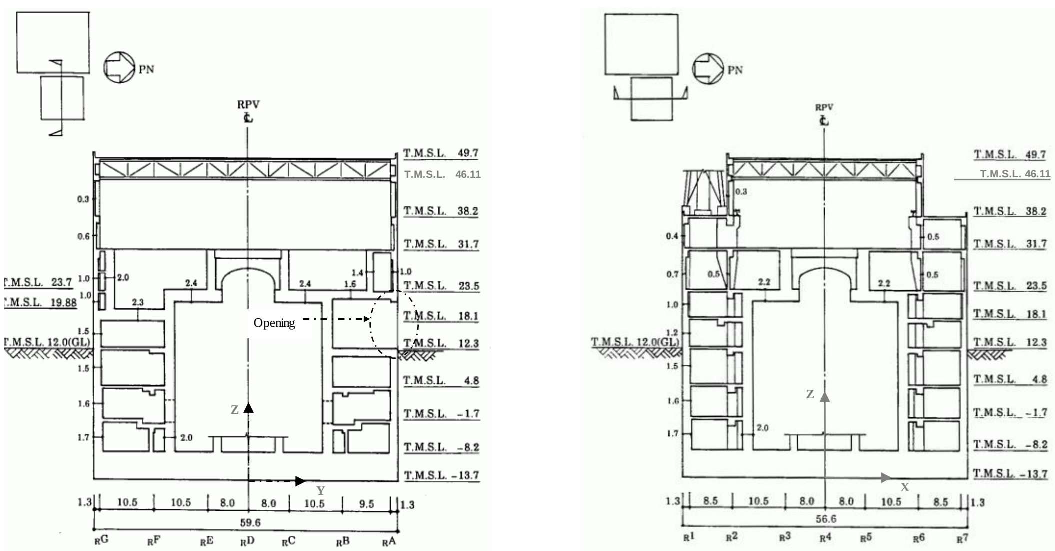
The Phase I of the KARISMA benchmark consists in modeling the Unit 7 Reactor Building (R/B), carrying out static analysis under static loads, identifying the fixed-base modal parameters of the structure and performing soil column analyses for the main shock and aftershocks of the NCOE. In this phase, the whole R/B structure is supposed to have a linear elastic behavior.

Unit 7 Reactor Building

Figure 2 shows the overall geometry of the Unit 7 Reactor Building where T.M.S.L. stands for “Tokyo Mean Sea Level” and PN indicates the Plant North (X direction) which is different from the geographic North. The building is constructed mainly in reinforced concrete except for the roof which is a steel structure. As can be seen in the figure, the Basemat and the 3 levels of the Basement are embedded in soil over 25 meters.

The structure of the Unit 7 Reactor Building is modeled in 3D using several types of finite elements depending on the geometry of the structural members. The Basemat of the building has a 5.5 m thickness with an almost square form. It is modeled with 8-nodes solid elements as shown in Figure 2(a), Because of its robustness, this part of the structure is considered elastic in the three phases of the benchmark.

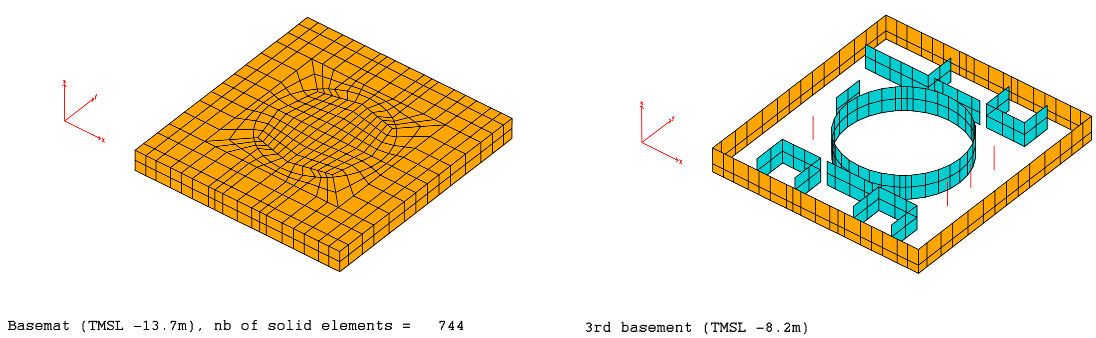
The 4 exterior walls, the interior walls as well as the Reinforced Concrete Containment Vessel (RCCV) are modeled using 4-nodes shell elements as shown in figure 2(b) which depicts the element mesh of the 3rd Basement. In addition to the common nodes between the connecting solid and shell elements, a special operator in CAST3M is used to ensure their rotational continuity.



(a) YZ section

(b) XZ section

Figure 2. Cross sections of the Unit 7 Reactor Building.



(a)

(b)

Figure 3. Finite element meshes of the Basemat and the 3rd Basement.

The columns and beams in the building are represented by beam elements. Their meshes are geometrically compatible with those of the floors and walls with connections which ensure the transmission of the moments perfectly. The floors are modeled with 4 or 3 nodes shell elements and the internal structure of the nuclear reactor is represented by simplified stick model given by the benchmark organizer. The complete model of the R/B structure is shown in figure 4. It is composed of 6265 elements. Reinforcement steel ratios for the main structure members as well as concrete and steel properties are given to the participants in the framework of the benchmark.

Once the model of the building formed, as requested by the benchmark, elastic analyses are performed under static loads to check its validity. Figure 5 shows the deformed fixed-base structure under gravity loading and unit acceleration (-1g) loading in the X and Y directions. These analyses show that the steel truss of the roof is much more flexible than the rest of the structure which are made of reinforced concrete.

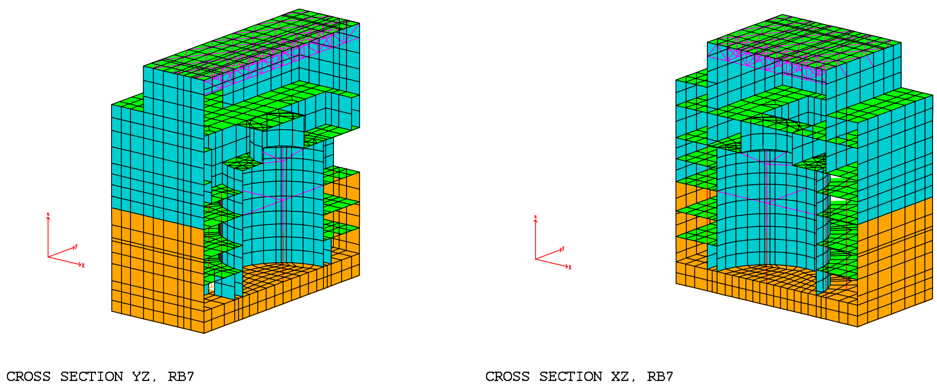


Figure 4. Finite element model of the Reactor Building.

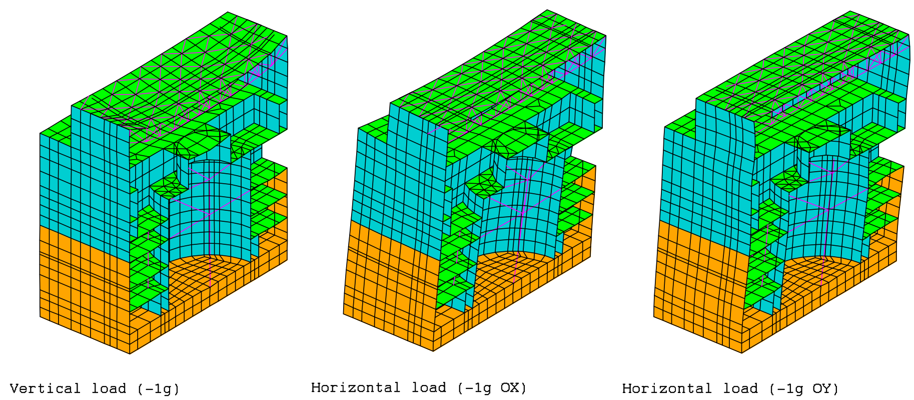


Figure 5. Structure deformation under static loadings.

Modal analysis has been performed on the fixed-base structure model using CAST3M. In the frequency range from 0 to 35 Hz, 379 vibration modes have been identified. Among them, many are local modes related to elements of the roof and exert very little influence on the overall response of the structure. The influence of each mode can be measured by their participating mass in X, Y and Z directions. Table 1 lists the first 12 modes with significant contribution to the participating mass.

Figure 6 presents the shapes of the first mode in each direction. We can note that in the X and Y directions, their first mode (modes N°1 and N°2 at 4.0 and 4.4 Hz respectively) are dominant with contributions over 70% to the participating mass whereas the first mode in the Z direction (mode N°3 at 4.9 Hz) is related to the roof vibration and represent just 1% of participating mass. Instead, we can see from table 1 that modes N°8, N°9 and N°11 (8.3~9.0 Hz) contribute significantly to the vertical motion of the structure.

Table 1: The first 12 modes of the Reactor Building.

Mode	Frequency (Hz)	Damping Ratio %	Modal participating mass ratios (%)			Modal participating mass ratios (%)		
			UX	UY	UZ	SumUX	SumUY	SumUZ
1	4.0374		70.405	0.00195665	1.24872E-05	70.405	0.00195665	1.24872E-05
2	4.4264		0.0034241	76.739	0.00920882	70.408	76.741	0.00922131
3	4.8903		0.0120503	0.00107754	0.95869	70.42	76.742	0.96791
4	5.8141		0.000721424	0.19234	0.0019503	70.421	76.934	0.96986
5	7.0856		0.4419	0.00323144	0.00144376	70.863	76.938	0.9713
6	7.4334		4.0124	0.0281005	0.50029	74.875	76.966	1.4716
7	7.4887		0.61506	0.0124235	0.0376366	75.49	76.978	1.5092
8	8.3131		0.44845	0.86342	15.192	75.939	77.841	16.701
9	8.5342		0.0467572	1.7375	9.0679	75.986	79.579	25.769
10	8.6407		2.7448	0.14746	0.55064	78.73	79.726	26.32
11	8.997		0.0860444	0.0392096	10.158	78.816	79.766	36.477
12	9.0271		0.56077	0.000229751	1.9744	79.377	79.766	38.452

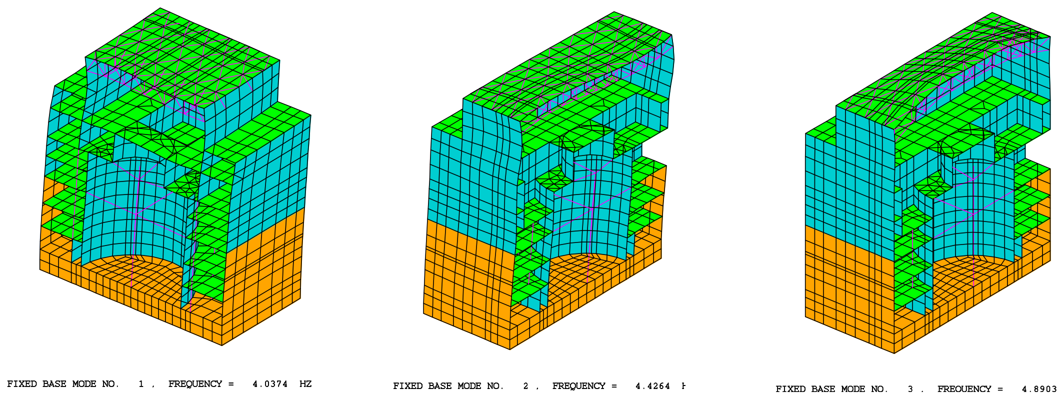


Figure 6. First mode in X, Y and Z directions.

Ground Soil

The soil near Unit 7 Reactor Building is considered as being horizontally stratified. Due to the procedure used for construction, no backfill soil is considered. The properties of soil layers, i.e. soil type, initial shear wave velocity Vs, unit weight γ, the Poisson's ratios ν and the initial shear modulus Go are given in Table 2. In order to take into account soil nonlinearity caused by the earthquake, strain dependant G/G_0 and damping ratio for sand, clay and rock layer are plotted in figure 7.

Soil column analysis calculates the seismic response of the free field by supposing that the seismic waves propagate vertically. This is done on a vertical column of soil representative of the geotechnical properties of the site. The goal is to obtain the soil model with shear modulus G and damping ratios compatible with the seismic motion of the free field at different depth of the ground soil.

To do this, we used the software EERA programmed by Bardet et al (2000) which is in fact a modern implementation of the code SHAKE. With this software, one uses a method known as “linear equivalent” which takes into account in a simplified way the effect of the nonlinearity of the ground soil. It consists in seeking a linear equivalent solution in an iterative way by using the curves presented in Figure 7.

Figure 8 shows the results of this analysis for the NCOE Main shock, i.e. the maximum shear strain, the modulus redaction G/G_0 and the damping ratio as a function of the depth of the soil. We can see that soil nonlinearity caused by the earthquake is concentrated in the surface layers of the first 10 meters with a maximum shear strain of 0.42%. The maximum shear modulus redaction reaches 70% and the maximum damping ratio obtained is 13%.

Table 2. Soil properties near Unit 7 Reactor Building.

Attitude T.M.S.L. (m)	Geological Layer	Soil type (Sand, clay or rock)	Shear Wave Velocity Vs (m/s)	Shear wave damping (%)	Primary Wave Velocity Vp (m/s)	Primary wave damping (%)	Unit Weight γ (kN/m3)	Poisson's Ratio ν	Initial Shear Modulus G0 (kN/m2)	Strain dependent soi properties
Grade Level (+12.0) +8.0	Sand	Sand	150		310		16.1	0.347	36 000	See below Table (Sand)
+4.0		Sand	200		380		16.1	0.308	65 700	
-6.0	Yasuda	Clay	330		1240		17.3	0.462	192 000	See below Table (Clay)
-33.0	Nishiyama	Rock	490		1640		17.0	0.451	416 000	See below Table (Rock)
-90.0		Rock	530		1700		16.6	0.446	475 000	
-136.0		Rock	590		1710		17.3	0.432	614 000	
-155.0		Rock	650		1790		19.3	0.424	832 000	
The free surface of the	Nishiyama	Rock	720		1900		19.9	0.416	1 050 000	N/A

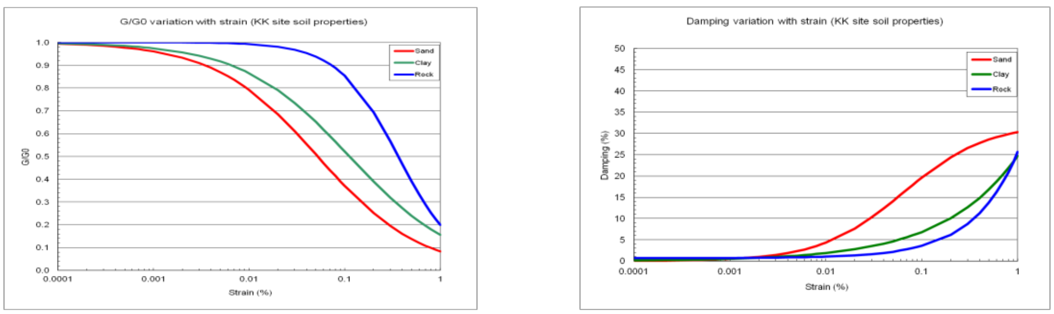


Figure 7. Strain dependent shear modulus and damping ratio.

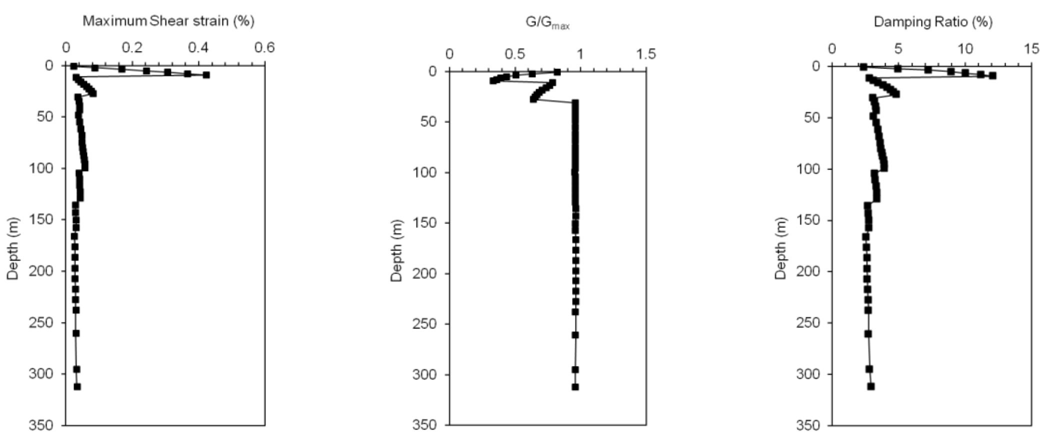


Figure 8. Results of soil column analysis, NCOE Main shock, X direction.

Soil-Structure Model with Viscous Boundaries

The coupled soil-structure model using CAST3M is presented in Figure 9. The mesh of the near-field soil is horizontally stratified with rather thin layers (1m thickness) in order to be compatible with the equivalent linear soil profile resulting from the soil column analysis. The mesh presented here has been optimized to reduce the number of elements while meeting the requirements on the dimension of the mesh (usually 5 times the dimension of the foundation due to the approximate nature of the viscous boundary) and the size of elements to ensure correct propagation of the waves in the vertical and radial directions.

Perfect contact between the structure and the soil is imposed by the common nodes of the interface. The final model is composed of about 150 000 finite elements. Viscous boundary is added on the lateral and bottom surface of the soil model to represent the far-field soil which extends to infinity.

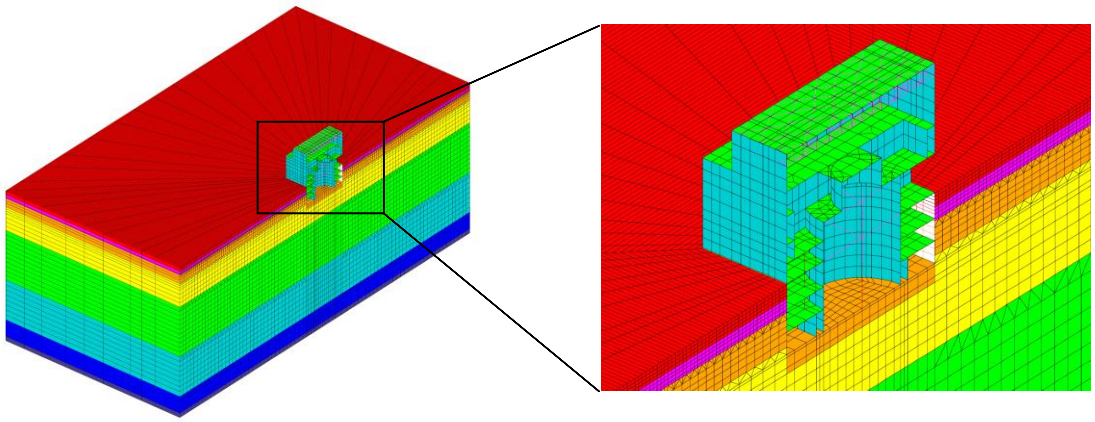


Figure 9. Coupled soil-structure model (half of the model plotted here).

BENCHMARK PHASE II : NCOE EARTHQUAKE RESPONSE

The Phase II of the benchmark consists in simulating by calculation the response of the Unit 7 Reactor Building during the main shock of NCOE. The behavior of the building is supposed to be linear elastic as no apparent damage has been observed on the main structure members after the earthquake.

Reference Soil Model and Input Motion

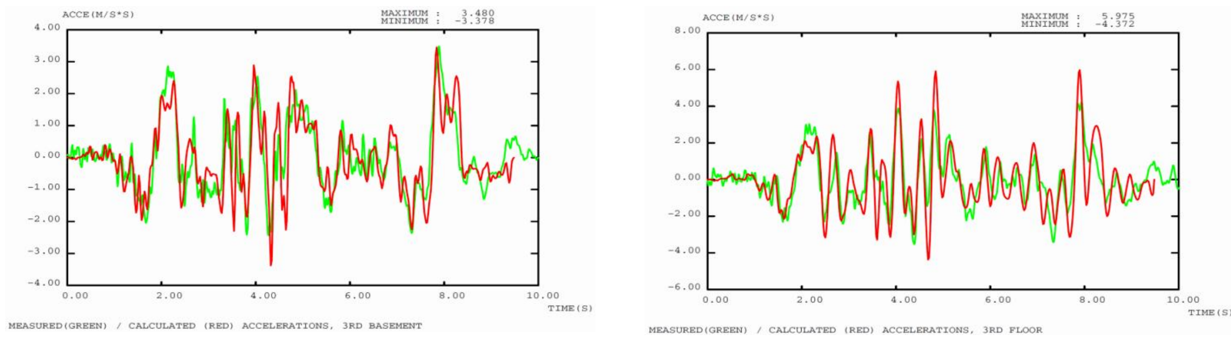
In order to be able to compare the results of the participants of the benchmark, a reference model of the soil near Unit 7 Reactor Building was given by the benchmark organizer. This model was obtained by an independent expert via soil column analysis in a similar way as we described above. The input motion for the SSI analysis is also given by the benchmark organizer. This signal was obtained from a free field surface recording at a location about 200 meters away from the Unit 7 Reactor Building The recording is de-convoluted to the bedrock outcrop (defined as the layer with Vs > 700 m/s) where the motion is supposed to be the same for the two locations.

Time Domain Analysis

A special procedure has been implemented in CAST3M to calculate from the input motion, the seismic loading to be applied on the soil model boundary. It is based on the deconvolution method by assuming vertical propagation of seismic waves in the free field soil.

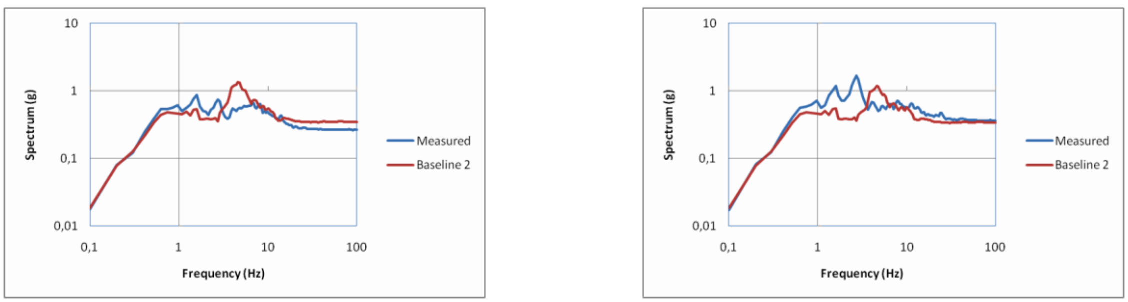
Using this procedure, SSI analysis is carried out in the time domain for the movements in X, Y and Z directions respectively. The time step used for the computation is 0.0025 second. Material damping of the soil and the structure is represented by the Rayleigh model.

In Figure 10, the calculated responses are compared with those measured by the two seismometers located on the surface of the Basemat (3rd basement) and on the 3rd Floor. One can note the good agreement between the numerical simulation and the measurement. Their response spectra are compared in Figure 11 where some differences are observed between the two curves. They show that the calculation over-estimates the frequency of the system.



(a) Basemat Surface (b) 3rd Floor

Figure 10. Response history in the Y direction (green: recording, red: calculation).



(a) Basemat Surface (b) 3rd Floor

Figure 11. Response spectra in the Y direction (blue: recording, red: calculation).

BENCHMARK PHASE III : MARGIN ASSESSMENT

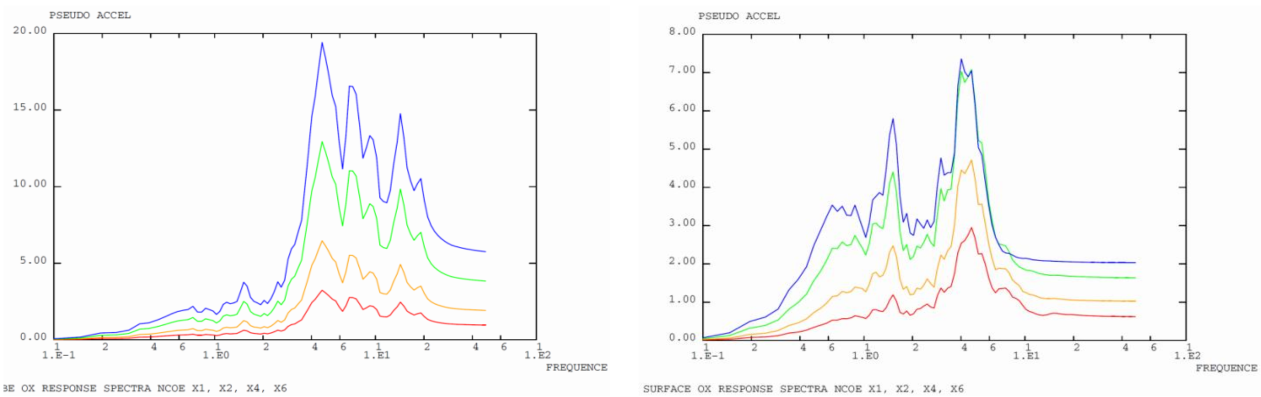
The objective of Phase III is to evaluate the seismic margin of the Reactor Building. That leads to nonlinear SSI analysis by increasing fictitiously the level of earthquake motion.

Increased Seismic Loadings

Four fictitious levels of seismic motion are specified by for phase III. They are defined on the bedrock outcrop by multiplying the amplitude of the signals: 1xNCOE, 2xNCOE, 4xNCOE, 6xNCOE. Figure 12 plots their response spectra on the outcrop of bedrock and on the soil surface. We see a saturation effect on the soil surface response due to the nonlinearity of the soil column, i.e. the peak amplitude for 6xNCOE is almost the same as that of the 4xNCOE on the soil surface.

Nonlinear SSI Analysis

For the fictitious high levels of seismic motion, the structure is supposed to exhibit nonlinear behaviors. CAST3M allows us to perform these nonlinear calculations. One just need to assign nonlinear constitutive laws to the elements of the structure. In order not to make the computation excessively heavy, only two principal lateral-resisting members, i.e. the exterior walls and RCCV are supposed to be nonlinear. They are modeled using multi-layered shell elements. Concrete walls are divided into 5 layers with smeared crack constitutive law. The reinforcements in the walls are represented by 4 layers of unidirectional materials with elasto-plastic law: for each face of wall, a layer for the horizontal reinforcements and a second layer for the vertical reinforcements.



(a) Bedrock outcrop (b) Soil surface

Figure 12. Response spectra for 1xNCOE, 2xNCOE, 4xNCOE and 6xNCOE (X direction)

The response time-history of the structure in the directions X, Y and Z are calculated simultaneously using CAST3M as the analysis is in the nonlinear domain. Gravity load is also taken into account prior to the dynamic analysis in the form of initial structural stress. Figure 13 shows the response of the 3rd Floor for the 4 levels of seismic signals. As expected, the amplitude of the response increases with the level of the input signal but their relation is not linear. For the level of 6xNCOE, generalized cracking can be seen on most part of the structure as shown in figure 14.

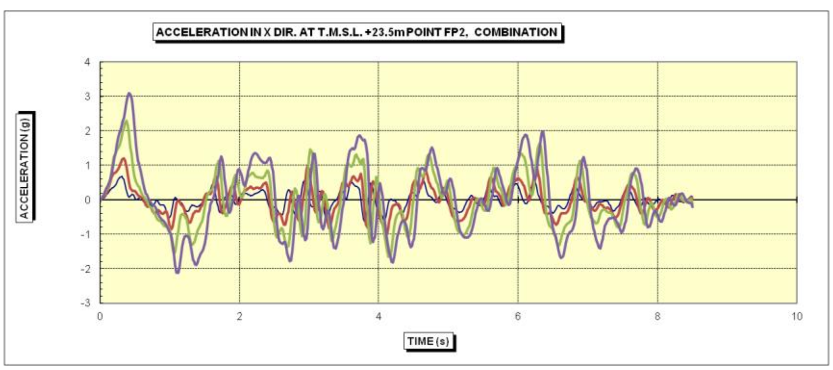


Figure 13. Response time-history for 1xNCOE, 2xNCOE, 4xNCOE and 6xNCOE (X direction)

In order to evaluate the seismic margin of the structure, the story-drift of several parts of the reinforced concrete walls were examined. For the level of 6xNCOE, the calculated story drift exceeds the usual criterion of failure of 1% for the reinforced concrete walls. One can thus consider according to this criterion that the structure reached its ultimate limit.

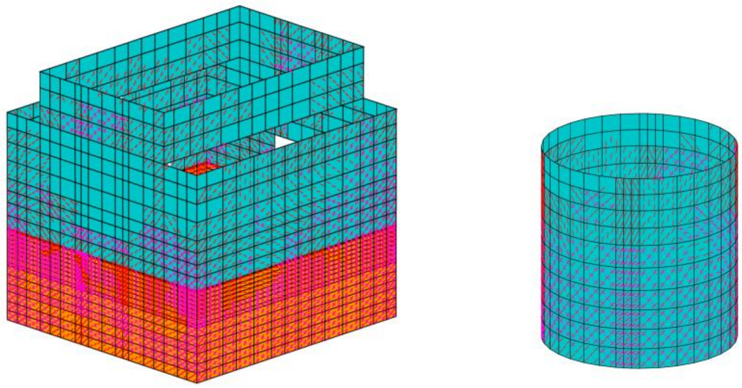


Figure 13. Generalized concrete cracking for 6xNCOE

CONCLUSION

This paper presents the contribution of the French CEA-IRSN team to the KARISMA Benchmark organized by IAEA following the 2007 NCOE Earthquake in Japan which affected severely the Kashiwazaki-Kariwa nuclear power plant.

This work consists of 3D finite element modeling for the structure and the near-field soil and the use of viscous absorbing boundary to represent the far-field soil (lateral sides and bottom). Time domain integration is carried out directly on the coupled soil-structure system. The analysis has given good results compared to the recorded structure response during NCOE earthquake. The procedure also allows us to perform nonlinear soil-structure interaction analysis under extreme seismic loadings by assuming ground motions 2, 4 and 6 times stronger than the NCOE earthquake. Seismic margin of the reactor building has been thus quantified.

The particularity of this work compared to that of the other participants is the fact that the method used is capable of tackling both the unboundedness of the soil media and the nonlinear behavior of the structure such as concrete cracking or reinforcement yielding.

ACKNOWLEDGEMENTS

The authors would like to express their deep thanks to the International Seismic Safety Centre (ISSC) of the International Atomic Energy Agency (IAEA) for organizing the KARISMA Benchmark and TEPCO Company for making data available on the Unit 7 Reactor Building.

REFERENCES

Lysmer J., Kuhlemeyer R.L. (1969). "Finite Dynamic Model for Infinite Media", *J. of the Engineering Mechanics Division*. Vol 91, EM4, pp 859-877

International Atomic Energy Agency (IAEA) (2009). "General specification for the KARISMA Benchmark Exercise". IAEA-EBP-SS-WA2- KARISMA-SP-0012009, Vienna

International Atomic Energy Agency IAEA (2011). "Guidance Document - PART 1: K-K Unit 7 R/B Structure, PHASE I, II & III", IAEA-EBP-SS-WA2- KARISMA-SP-002, Vienna

Bardet J.P., Ichi K., Lin C.H. (2000). "EERA a computer program for Equivalent-linear site response analysis of layered soil deposits" University of Southern California, Department of Civil Engineering, August 2000