# Seismic analysis with Soil-Structure Interaction KARISMA Benchmark

**F. TURPIN, N. BONFILS, N. SUIN, N. HUMBERT, I PETRE-LAZAR,**
*EDF/SEPTEN Dynamics and Earthquake Engineering*
*12 - 14 avenue Dutrievoz, 69628 VILLEURBANNE, FRANCE*

**SUMMARY**
On July 16 2007, the Kashiwazaki Kariwa nuclear power plant has been affected by a strong earthquake (moment of magnitude 6.6), the Niigataken-Chuetsu-Oki Earthquake (NCOE).This nuclear power plant, the biggest one in the world, is located at about 16km from the epicentre. The large amount of recordings and observations collected during the earthquake and its aftershocks raised the idea of organizing a benchmark on seismic behaviour (KARISMA Benchmark).
Through his participation in this benchmark, the EDF main objective is to challenge its advanced calculation methods by comparing the computations results with the recordings and worldwide participants.

*Keywords: Benchmark, Soil-Structure Interaction, Material Nonlinearities, Finite Element Modeling*

## 1. INTRODUCTION

The results presented in this article are part of the KARISMA benchmark (Kashiwazaki-Kariwa Research Initiative for Seismic Margin Assessment, [8]). This benchmark has been organized by the IAEA (International Atomic Energy Agency)
On July 16$^{th}$ 2007, the Kashiwazaki Kariwa nuclear power plant has been affected by a strong earthquake (moment of magnitude 6.6): the Niigataken-Chuetsu-Oki Earthquake (NCOE).
During this strong earthquake, recordings have been collected. These recordings have revealed a seismic level beyond the seismic design. Nevertheless, no significant damages have been observed on the site.
One of the main goals of this study is to evaluate the classical numerical analyses relevance and their ability to represent the structural and soil response beyond the design level. Moreover, thanks to this benchmark, EDF can compare its results with recordings and with the results obtained by the other participants.
The KARISMA benchmark hence constitutes an opportunity to challenge the computations methods used in nuclear industry with a real case.
The finite element code used for structural behavior is Code_Aster : a finite element code developed by EDF Research and Development Department. The soil structure interaction issue is computed using Code_Aster/ProMiss3D. Finally, the site effect is taken into account by using CyberQuake software (deconvolution, linear equivalent characteristics…).

The study is divided into two main parts:

- A first part focuses on the structural elastic linear analysis, the soil response and the soil-structure interaction method;
- A second part attempts to account for material nonlinearities in the model;

## 2. ELASTIC LINEAR ANALYSIS

In this part, the objective is to validate the structural model and to present the soil structure interaction method used for the elastic linear analysis. In addition, a soil analysis will presented in order to characterize the seismic site effects.
Indeed, one of the challenges of this study is to represent correctly the coupling between soil and structure (Soil Structure Interaction). Calculations have been done using a “best estimate” analysis, characterized by the frequency coupling method.
The computation codes are Code Aster for the structural calculation, ProMISS3D for the soil structure interaction calculation and CyberQuake to compute the input signals at free field or raft elevation.

## 2.1 Modeling

*2.1.1 Structure*
The structure studied in this benchmark is the reactor building of the Kashiwazaki Kariwa nuclear power plant. It is a 60 meters high building with an embedment of about 30 meters.The main structural parts of the reactor building are:

| Model characteristics | |
|---|---|
| Number of nodes | 12600 |
| Shells elements | "Love-Kirchoff" modeling |
| Number of elements | Quadrangular 9700 |
| | Triangular 2600, Edges 3300 |
| Beam elements | Euler beam (R/C beams and columns) |
| | Timochenko beam (stick model of R/B) |

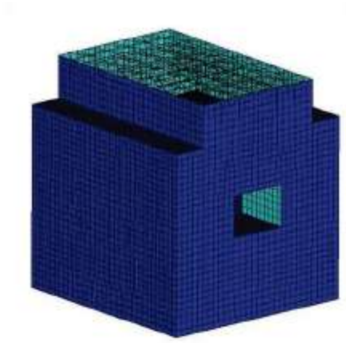

**Figure 1** Structure modeling

- Basemat
- Exterior walls
- Reinforced Concrete Containment Vessel (RCCV)
- Interior walls and auxiliary walls
- 8 main floors; composed of mainly reinforced concrete slabs and beams, locally few steel beams at same elevations
- Intermediate reinforced concrete column
- Steel roof structure

Shell elements have been chosen for walls, floors, RCCV and basemat; beams and bars elements for columns, Reinforced Concrete beams, structural steel frame and reactor vessel (see Figure 1). A hypothesis of linear elasticity behaviour for structural elements has been adopted in this part.

*2.1.2 Soil*
The soil has been modeled with a stratified semi-infinite medium with degraded soil characteristics according to a pseudo-elastic approach. G/Gamma curves were provided by the benchmark organization.

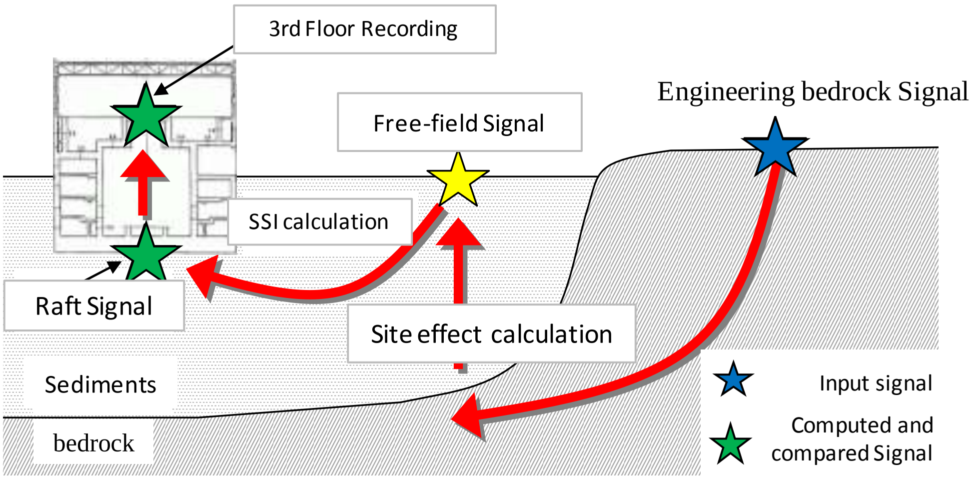


**Figure 2** Site effects and SSI methodologies

*2.1.3 SSI strategy*

Within the framework of linear elasticity, the frequency method offers the possibility to account for the embedment of the structure. In addition, this method takes into account the frequency dependence of the impedance functions. The coupling between Code_Aster and ProMiss3D has been used to perform the computations. A free field input signal (at 0m) is considered here. It has been computed by means of transfer functions between the bedrock level and the free field at 0m (see Figure 2).

### 2.2 Results presentation and analysis

All the results presented in this article refer to X-direction. Indeed, the same conclusions may be done for the other directions.

*2.2.1 Soil analysis*

The analysis of the transfer function between the signals recorded at the bedrock level and the free field permit us to determine the seismic site effect (see Figure 3 Transfer function between raft elevation (-26,00m) and engineering bedrock ).

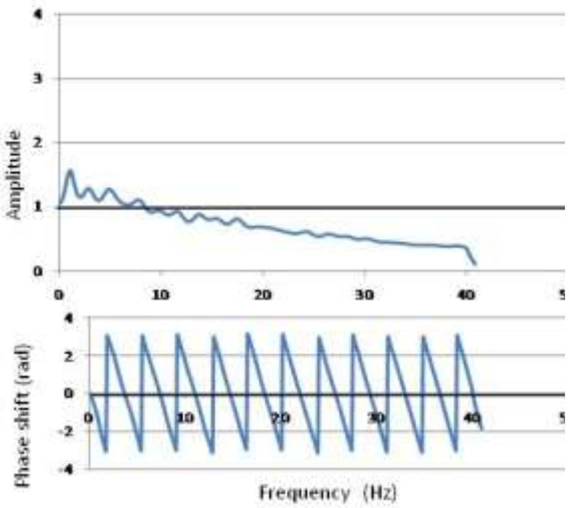


**Figure 3** Transfer function between raft elevation (-26,00m) and engineering bedrock

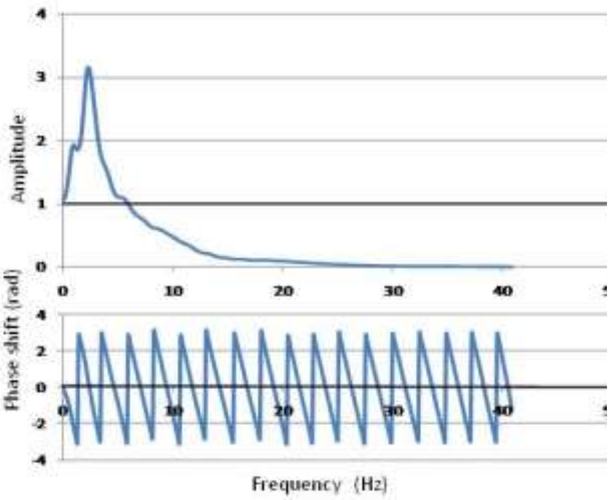


**Figure 4** Transfer function between Free Field and engineering bedrock

An important seismic site effect may be observed in the free field at 0m level (see Figure 3 Transfer function between raft elevation (-26,00m) and engineering bedrock ). The resonance frequency associated to this site effect is 2.5 Hz. It corresponds to the vibration frequency of the 7.5 upper meters of the soil column. Indeed those upper meters consist of strongly degraded sediments (Vs = 75 m/s, H = 7.5m → Vs/(4H) = 2.5 Hz).  On the other hand, high frequencies from 7 Hz are absorbed. This absorption is due to the nonlinear behaviour of the upper part of the soil column constituted of both clay and sediment (see Figure 5).

On the contrary, the transfer function between the bedrock and the raft elevation in the free field revealed that there is no particular seismic site effect. A relative absorption of high frequencies above 40 Hz may be observed (see Figure 3). This phenomenon may be attributed to the high level of the seismic input signal. Indeed, it causes high damping phenomenon, even in the Nishiyama rock.

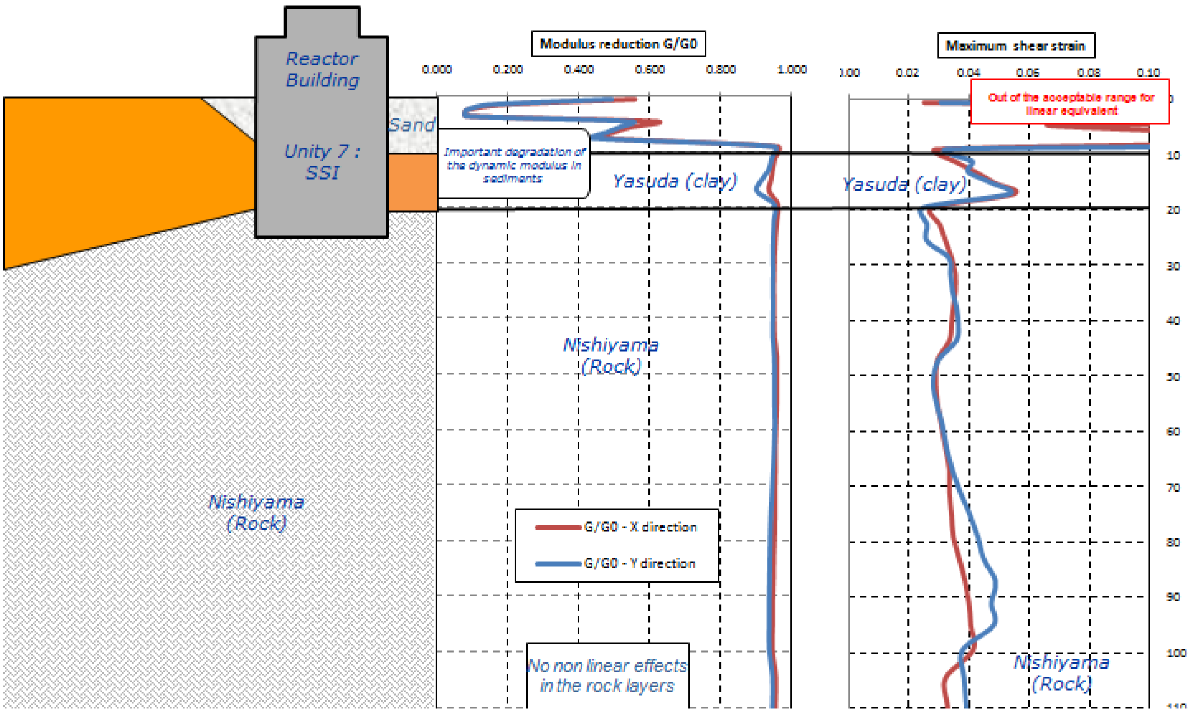


**Figure 5** Shear modulus deterioration and maximum shear strain in the soil

*2.2.2 Structure analysis*

For the structural analysis the input motion is the data recorded at the raft level during the main shock of the earthquake. The output data is the spectral acceleration observed at the third floor elevation.

In such an analysis, site effect and kinematic interaction are dismissed. Only both structural modeling and inertial soil structure interaction have an impact on the result.

The structural behaviour has been characterized by means of transfer functions between the raft and the third floor. Acceleration values at the third floor are then obtained by application of the transfer function to the recorded input signal.

The model can be validated by making comparisons between the computed spectra and the recorded spectra at the third floor (see Figure 6).

Furthermore, this comparison helped us to validate the linear elastic hypothesis used for constitutive laws of structural elements. The acceptable similarity of the two spectra shows that the structure has not reached its post-elastic behaviour.

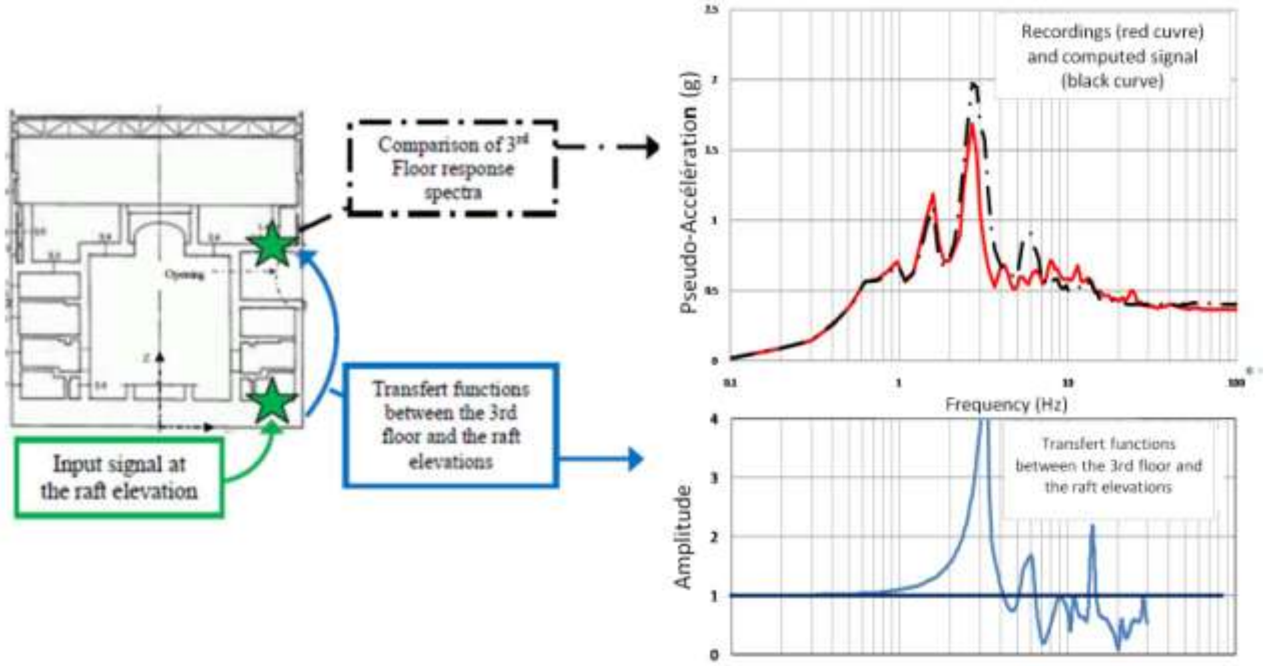


**Figure 6** Modeling validation process by raft input signal

This structural analysis is consistent with benchmark results of teams that used a control point at the raft level (four teams of the benchmarck). As shown in Figure 7, results from best-estimate analysis of other participants are fairly similar with our computed signal and the recording signal (in term of spectral acceleration). Our inertial interaction modeling appears to be adequate to represent the global behaviour in an acceptable way.

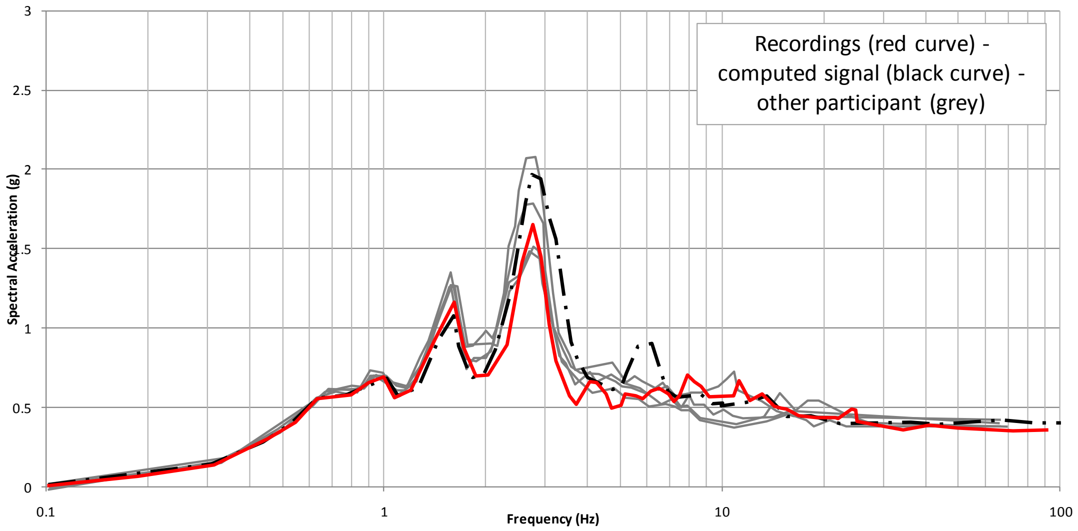


**Figure 7** Floor response spectra at the 3rd floor elevation (X direction), computation with a control point at the raft elevation, comparison with other participants (4 participants).

*2.2.3 Complete calculation with site effect and SSI*

In Figures 8 and 9, computed signals with frequency coupling method are compared with recordings and participants results. Note that no control points are used at the raft and, seismic input is based on computed bedrock motion. For some participant results (five participants), a peak around 4.5Hz at the raft level can be observed for the computed spectra, and does not appear in the recording spectra. Differences with recordings are assumed to mainly come from uncertainties in soil modeling and from the incident signals which significant frequency content is around this value. The benchmark input signal does not seem to be able to capture the real SSI modes. This could be due to the way to process the bedrock signal, based on a deconvolution from another unit of Kashiwazaki site (unit 5). Moreover, contrary to the computation with the raft elevation control point (see Figure 7), strong discrepancies in the results obtained by the participants may be observed.

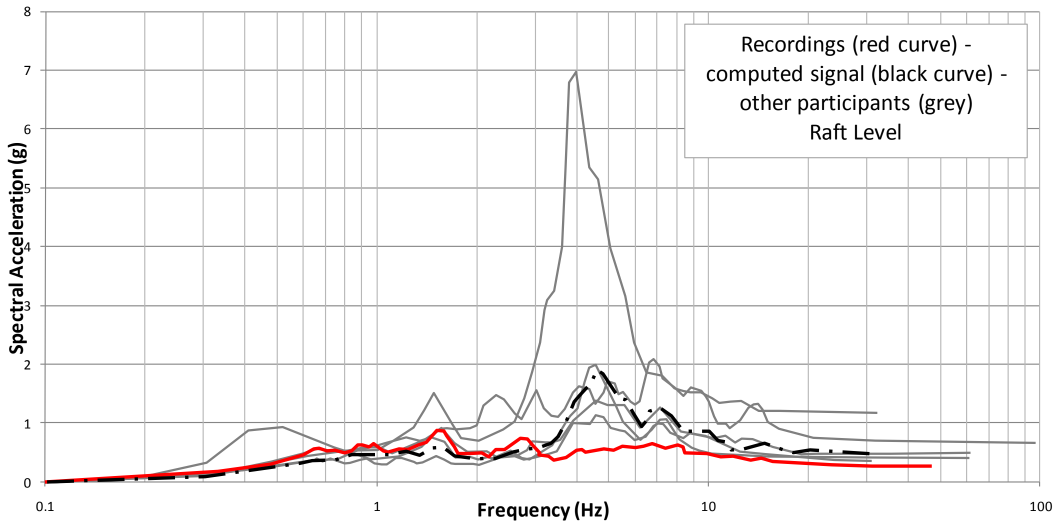


**Figure 8** Floor response spectra at the raft elevation (X direction), computation based on the bedrock motion, comparison with other participants (5 participants).

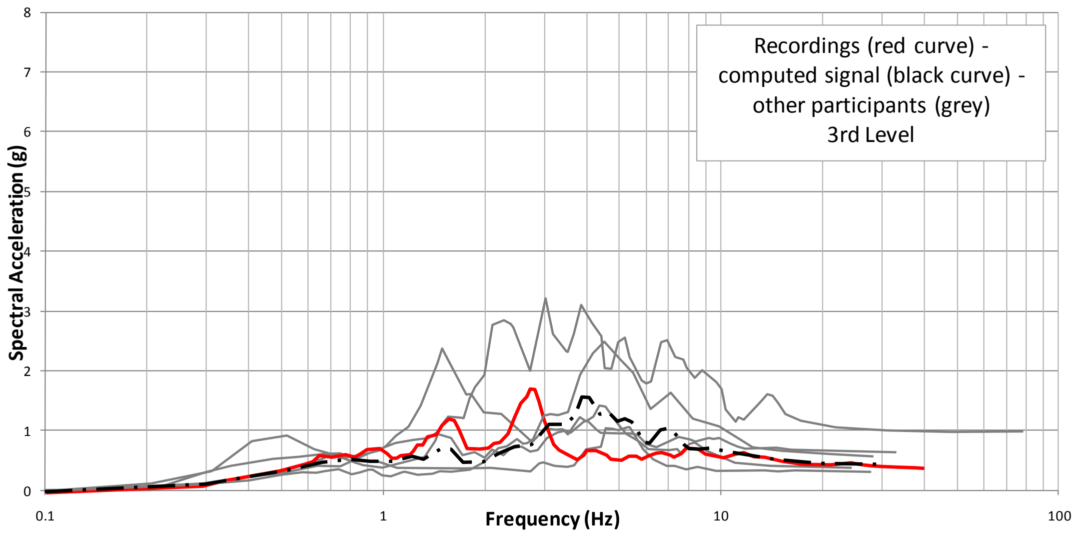


**Figure 9** Floor response spectra at the third floor elevation (X direction), computation based on the bedrock motion, comparison with other participants (5 participants).

## 3. NONLINEAR STUDY

Another challenge is to represent the non-linear behaviour of the structure in order to perform a Margin Assessment of the reactor building. This margin assessment consists in submitting the reactor building to an increasing seismic loading (up to six times the recorded free field signal).

Two non-linear phenomena have been taken into account in the model: damage and plasticity. A generalized constitutive law has been employed to model the damage of reinforced concrete. This constitutive law is modeling the damage under membrane stress and bending stress using « homogenized » parameters.

### 3.1 Material Nonlinearities

Material nonlinearities have been applied to selected areas of the structure. Hence, main shear walls and main floors exhibit a nonlinear behaviour. A linear elastic hypothesis has been preserved for the other structural elements (beams, columns, and steel frame).
The modeling of reinforced concrete nonlinear behaviour has been made through the implementation of a generalized law: GLRC_DM (Generalized Law for Reinforced Concrete): see Figure 10.
Nonlinear phenomena, such as plasticity or damage, are directly in relation to the generalized strains (extension, curvature, distortion) and the generalized stresses (forces of membrane, of bending and cutting-edges). Thus, this constitutive law can be applied to plate or shell finite-element. That makes it possible to reduce, compared to a multi-layer approach, time CPU as well as memory. The advantage compared to the multi-layer shells is even more important, when one of the components of the plate behaves in a quasibrittle way (concrete, for example), since the total model makes it possible to avoid the problems of localization.
Behaviour law GLRC_DM models the damage under membrane and bending stresses for reinforced concrete plates, using "homogenized" parameters.

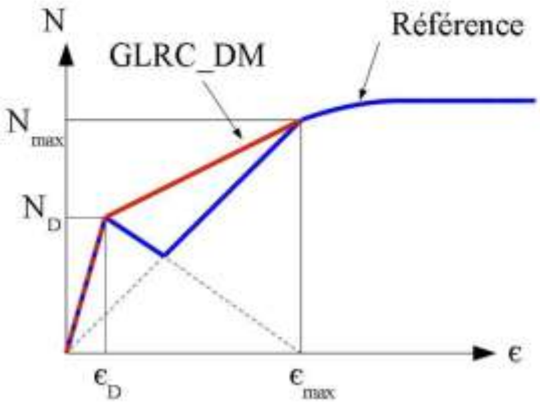


**Figure 10** Non linear constitutive law used for Reinforced Concrete

In addition, the plasticity for steel reinforcement has been introduced in the model thanks to a numerical coupling between damage and elastoplastic model in terms of generalized stresses and strains. A linear isotropic hardening elastoplastic model has been considered in this study.

### 3.2 Boundary Conditions

Two types of boundary conditions have been considered here. On the one hand the raft is supposed clamped. On the other hand, soil-structure interaction is taken into account through the setting of "soil springs" via a linear equivalent model. The building embedment has not been considered in this nonlinear study.

### 3.3 Nonlinear analysis

Two different nonlinear analyses have been carried out:

- A pushover analysis
- Dynamic analyses

For the first step of the nonlinear study, a pushover analysis of the reactor building has been carried out. A lateral uniform load distribution is imposed to the overall structure (from the base to the roof) so as to represent the inertial forces during an earthquake. This lateral load is then increased until

displacement at a control point reaches a certain value.
A force/displacement curve is then extracted from this nonlinear quasi-static analysis. The displacement at the center of mass is then plotted with base shear to obtain the global capacity curve.
The capacity curve is finally compared to the demand curve to estimate the earthquake induce displacement demand for this structure.
Note that for a pushover analysis, it is assumed that the structure is essentially controlled by a single deformation mode.
For the second step, "time history" analyses have been performed for increasing input seismic signals (1XNCOE, 2XNCOE, 4XNCOE, 6XNCOE). For each analysis (pushover and "time history"), two types of boundary conditions have been considered. The basemat is clamped. Soil-structure interaction is accounted for with the "soil spring" method.

### 3.4 Results

The results obtained by the benchmark participants for the pushover analysis are presented in Figure 11. In this figure, EDF has presented the results obtained for the pushover analysis with soil-structure interaction consideration. Those results are close to the mean values of the participant results.

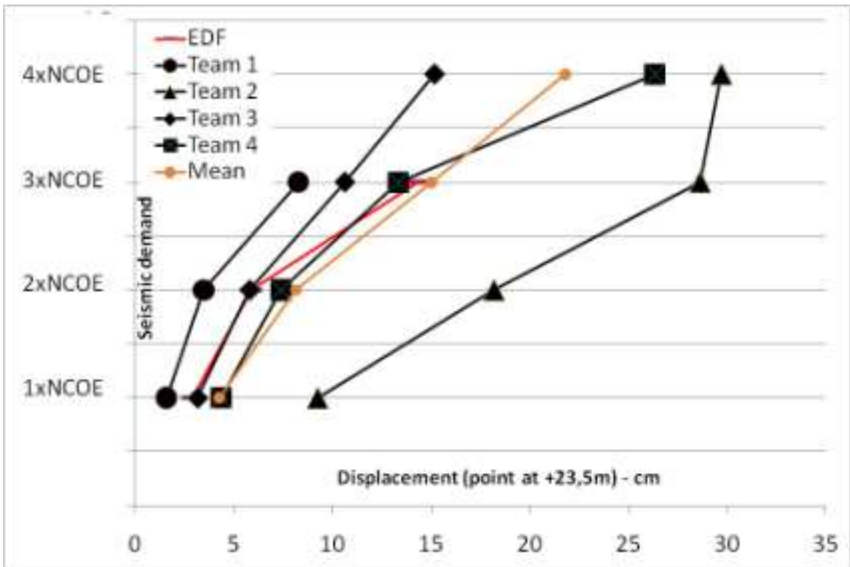


**Figure 11** Displacement at point CP2 (+23.5m) obtained by different participants and for different seismic demand levels

Regarding "time history" analysis with "soil springs", the results obtained by EDF team are consistent with recordings (Figure 12 left). For higher seismic levels (Figure  right), all the results exhibit a strong dispersion compared to the mean values. This phenomenon is due to the fact that material nonlinearities have been taken into account by the participants in many ways. Indeed, each participant has adopted his own strategy to model concrete damage or reinforced bars plasticity.

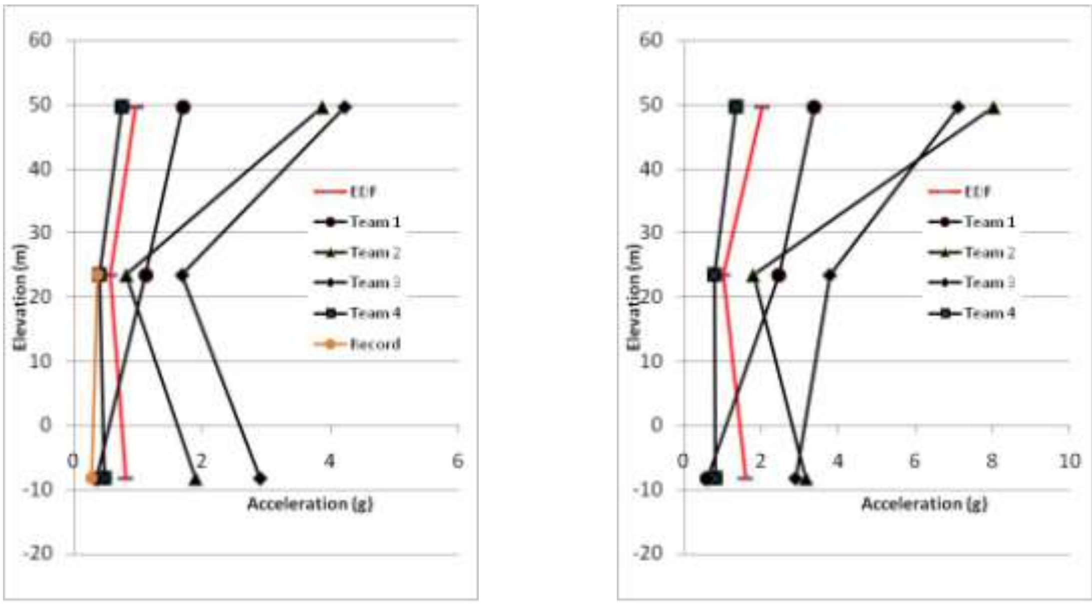


**Figure 12** Acceleration values at recorded points for different elevations for two seismic levels: 1xNCEO (left) and 2xNCOE (right)

## 4. CONCLUSION

This benchmark was a good opportunity for EDF to challenge its computation methods. Indeed, material nonlinearities, soil-structure interaction method have been applied on a real case study.
Firstly, the soil analysis showed that the upper part of the soil column has been strongly solicited and the equivalent linear method hypothesis may be questioned. Furthermore, this benchmark has revealed the importance of the input signal on the results. Differences between recorded and computed signals have been observed. Many participants have observed this phenomenon and have concluded to the uncertainties in the soil characteristics and above all, to the input signal.

Secondly, the structural analysis has shown that there was no real incursion in the nonlinear area. Indeed a comparison has been made between the recorded signal and the elastically computed one. This relatively good similarity between these signals led us to this conclusion.
Finally, this benchmark was a possibility to compare our nonlinear analysis methods with international practices. Material nonlinearities have been applied to selected areas of the structure. Hence, main shear walls and main floors exhibit a nonlinear behaviour. Nonlinear results obtained by EDF are coherent close the mean values of the participants. However strong discrepancies have been noticed for the nonlinear analysis.

## 5. REFERENCES


BRGM. Cyberquake website. http://www.brgm.fr/pdf/logiciels/CyberQuake.pdf.
Clouteau, D. Miss 6.4 Manuel scientifique. http://www.mssmat.ecp.fr/structures/perso/miss, 2005.
EDF R&D. Code_Aster website. http://www.code-aster.org.
EDF R&D Code_Aster User Manual : Civil engineering calculations with seismic loading, doc U2.06.10.
EDF R&D Code_Aster, Constitutive Law GLRC_DM, doc R7.01.32
Koechlin, P., and Potapov, S. (2007). Global Constitutive Model for Reinforced Concrete Plates. Journal of Engineering Mechanics *133*, 257-266
Markovic, D., Reinforced concrete structures under extreme loading:Stress resultant Global Reinforced Concrete Models (GLRC), ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, June 2007
IAEA, GUIDANCE DOCUMENT PART I - K-K Unit 7 R/B Structure - PHASE I,II and revised III - rev05 of February 2012