BENCHMARK RESEARCH FOR SEISMIC RESPONSE ESTIMATION OF BASE-ISOLATED CRUAS NPP

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ABSTRACT

This study aims to evaluate the seismic response of the isolated Cruas nuclear power plant as part of the SMATCH benchmark program. Considering the deterioration of the seismic isolation device installed in 1980, the current mechanical characteristics are estimated and used for the seismic response evaluation. The results are generally in good agreement with the nuclear power plant response to the actual earthquake that occurred in 2019, and it is expected to contribute to the seismic safety evaluation of the isolated nuclear power plant.

INTRODUCTION

Seismic isolation technology is being used as an alternative to dramatically improve the seismic safety of nuclear power plants (Jung *et al*., 2022). However, not many cases of seismic isolation are being applied to nuclear power plant structures worldwide. Among them, the Cruas nuclear power plant in France is a representative example. In particular, the Cruas nuclear power plant was affected by the Le-Teil earthquake that occurred in 2019, and it is a very rare case in which a base-isolated nuclear power plant was affected by an earthquake and seismic response data was measured. An international benchmark called SMATCH (IRSN *et al*., 2023) was launched to numerically predict and evaluate this data through seismic response analysis, and our research team is participating in this benchmark and conducting research.

The characteristics of the elastomeric base isolators installed in the Cruas nuclear power plant are assumed as a bilinear model, and the main characteristics of the current base isolators are estimated by considering the effects of aging and applied to the seismic response analysis. The seismic response analysis results are compared with sensor responses from several locations within the nuclear power plant for evaluation. The results are compared based on the acceleration time history due to the earthquake and the response spectrum at the sensor locations. The results obtained by the numerical analysis are generally in good agreement with the measured responses caused by the actual earthquake, and it is a good opportunity to derive and evaluate the responses of a very rare base-isolated nuclear power plant.

NUMERICAL MODEL FOR BASE-ISOLATED NPP

Structural model for Cruas nuclear power plant

As part of the benchmark program, a numerical model was constructed to predict the seismic response of the Cruas nuclear power plant. The numerical model was constructed based on the model provided by SMATCH. The original model of the Cruas nuclear power plant was developed in EDF based on CODE-ASTER. The numerical model developed for the CODE-ASTER platform was converted to the SAP2000

(CSI, 2013) platform and consists of approximately 110,000 nodes, 13,000 frame elements, 150,000 shell elements, and 1,800 seismic isolation device elements.

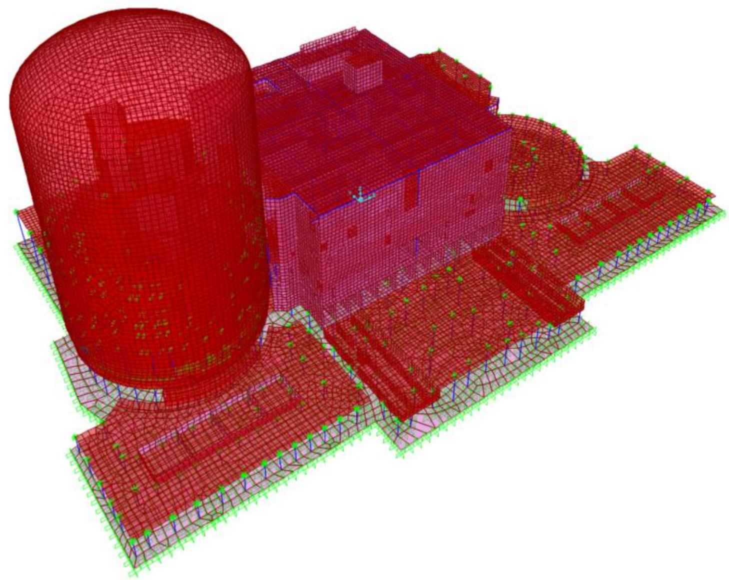


Figure 1. Numerical model of Cruas nuclear power plant

Base isolator for Cruas nuclear power plant

The Cruas nuclear power plant is designed with elastomer bearings as the standard seismic isolation units. The seismic isolation units are designed to satisfy the horizontal natural frequency of 1 Hz (Labbé, 2013; Vaidya and Bazan-Zurita, 1988), and the standard unit has dimensions of 500 mm in length and width, and a total elastomer thickness of 40.5 mm (three layers of 13.5 mm elastomer). Each seismic isolation unit is mounted on a concrete pedestal, and each pedestal supports 2, 4, or 8 seismic isolation units. As a result, about 1,800 seismic isolation units, mounted on about 400 pedestals, support the raft on which the power plant is installed.

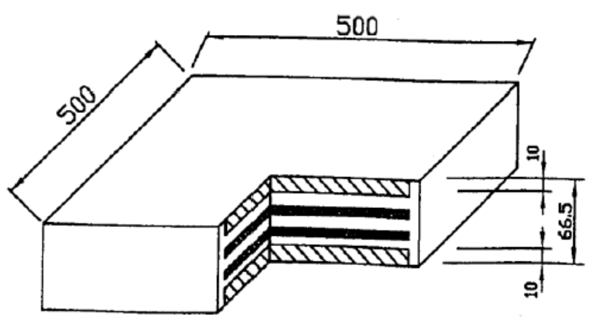


Figure 2. Standard isolation unit for Cruas nuclear power plant (IRSN *et al.*, 2023)

To account for the aging of the seismic isolation device installed in 1980, we utilized the deterioration curve provided by the SMATCH program (IRSN et al., 2023). The initial shear modulus and the deterioration-induced shear modulus ratio (Gd/Gd0) over time can be estimated by the following equation, which is illustrated in Figure 3.

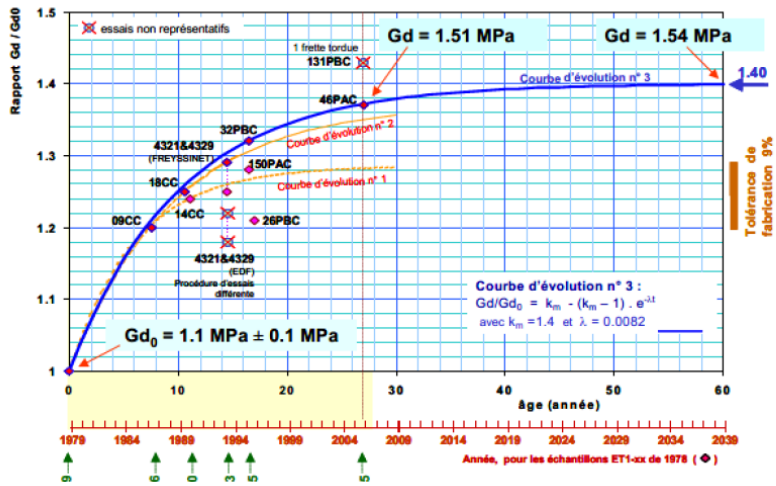


Figure 3. Isolators aging curve with dynamic module ratio (IRSN *et al.*, 2023)

$$G_d/G_{d_0} = k_m - (k_m - 1)e^{\lambda t} \tag{1}$$

where k_m is 1.4, λ is 0.0082, and t is month.

The behavior of the seismic isolator is assumed as a bilinear model, and the mechanical properties are determined using design information in the literature (Labbé, 2013; Vaidya and Bazan-Zurita, 1988; Coladant, 1991) and experimental information provided by the SMATCH program. First, the effective stiffness of the seismic isolator at the time of installation is calculated using the design target horizontal frequency (f_n=1 Hz) and the mass of the numerical model (4.5E+8 kg) using the following equation.

$$K_{eff(isolator\ unit)} = \frac{M(\text{total mass})}{N(\text{number of isolator})} \times (2\pi \times f_n)^2 \tag{2}$$

Next, the horizontal first stiffness was defined using the shear modulus obtained from the white noise test performed in 2008 (IRSN *et al.*, 2023). The shear modulus (G_d) obtained at a very small displacement was 5.36 MPa, and the result of calculating the horizontal first stiffness using the following equation was 33.09 kN/mm.

$$K_1 = \frac{A \times G_{d(\text{white noise test})}}{h} \tag{3}$$

where K_1 is first stiffness, A is area of isolator, and h is total thickness of elastomer. Then, the horizontal secondary stiffness (K_2, post-yield stiffness) is determined based on the data obtained from the progressive distortion test performed in 1980 (IRSN *et al.*, 2023). The shear modulus obtained for horizontal displacements of 0.6 mm to 1.4 mm are shown in Table 1. The horizontal secondary stiffness of the seismic isolator is assumed to depend on the shear modulus obtained from the progressive distortion test, and the results in Table 1 are converted to force-displacement data using Equation (4), and the slope of the fitted curve is defined as the secondary stiffness.

Table 1: Progressive distortion test of isolator unit (IRSN *et al.*, 2023).

Distortion [mm]	0.6	0.8	1.0	1.2	1.4
Gd [MPa]	1.28	1.19	1.13	1.08	1.04

$$F_H = \frac{G_d A}{h}\delta \tag{4}$$

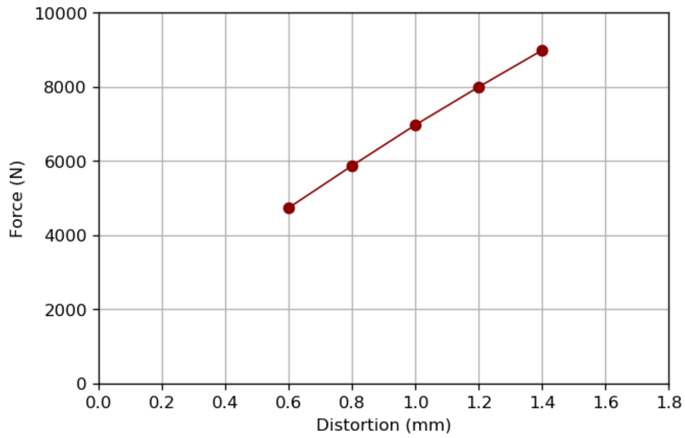


Figure 4. Isolators aging curve with dynamic module ratio

where F_H is horizontal force, G_d is shear modulus from progressive distortion test, and δ is distortion. Next, the characteristic strength (Q_d) is calculated. It is assumed that the maximum displacement for deriving the target frequency of 1 Hz at the design stage was calculated based on the 100% shear strain of 40.5 mm (h), which is the thickness of the elastomer of the seismic isolator. The characteristic strength (Q_d) is calculated using the following equation based on the values of the effective stiffness (K_{eff}) and the secondary stiffness (K_2).

$$Q_d = h(K_{eff} - K_2) \tag{4}$$

Among the parameters of the isolation unit obtained through the above procedure, the effective stiffness (K_{eff}), characteristic strength (Q_d), and secondary stiffness (K_2) are recalculated by multiplying them by the aging factor (1.393) for the time in which the Le-Teil earthquake occurred. The change in the first stiffness derived from the white noise test performed in 2008 is assumed not to have a significant effect on the dynamic response of the overall structure, so the existing value is applied as is. The mechanical characteristics of the base isolation unit organized according to the above procedure are as follows.

Table 2: Mechanical properties of base isolation unit

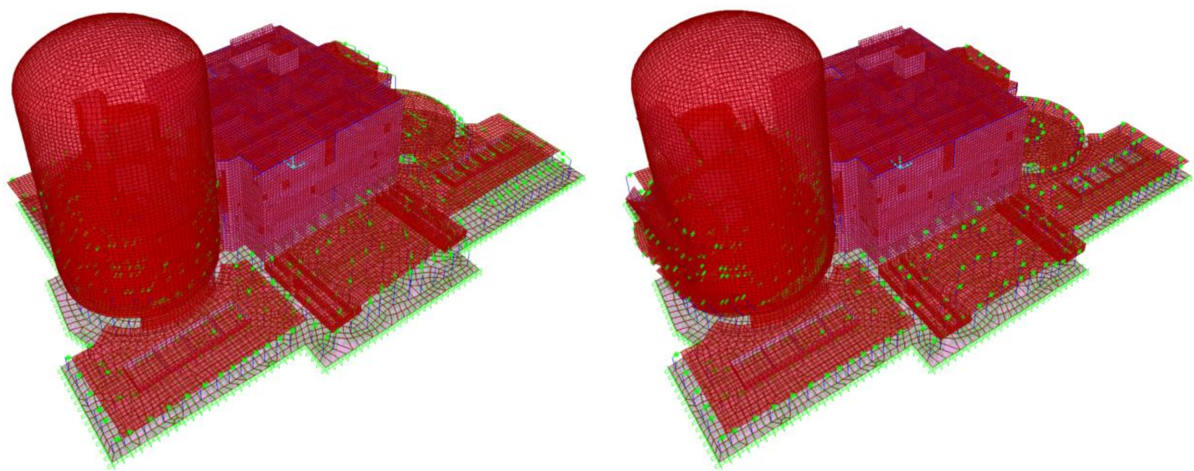
Property	**Value**
K_1 (1st stiffness)	3.309E+7 (N/m)
K_2 (2nd stiffness)	7.394E+6 (N/m)
Q_d (characteristic strength)	2.567E+5 (N)
K_{eff} (effective stiffness)	1.373E+7 (N/m)
Behavior	bilinear

As described above, approximately 400 concrete pedestals are installed with 2, 4, and 8 seismic isolation units. Therefore, the mechanical characteristics of the isolator elements are determined so that they have 2, 4, and 8 times the stiffness of the seismic isolation unit by arranging the link elements at each pedestal installation location.

SEISMIC RESPONS ANALYSIS OF CRUAS NUCLEAR POWER PLANT

Mode analysis for base-isolated nuclear power plant

Seismic response analysis is performed using the numerical model of the isolated nuclear power plant described in the previous section. An isolation device was configured using the rubber isolator link element of SAP2000, applying the characteristics in Table 2. seismic response analysis was performed using the Fast Nonlinear Analysis (FNA) method, which is a modal analysis using equivalent stiffness available in SAP2000. The results of the modal analysis show that the horizontal major frequencies are 1.18 Hz in the y direction and 1.27 Hz in x direction. The mode shapes of the two horizontal modes are shown in Figure 6 as below.



(a) (b)

Figure 5. (a) 1st and (b) 2nd mode shape of base-isolated NPP model

Seismic response analysis for base-isolated nuclear power plant

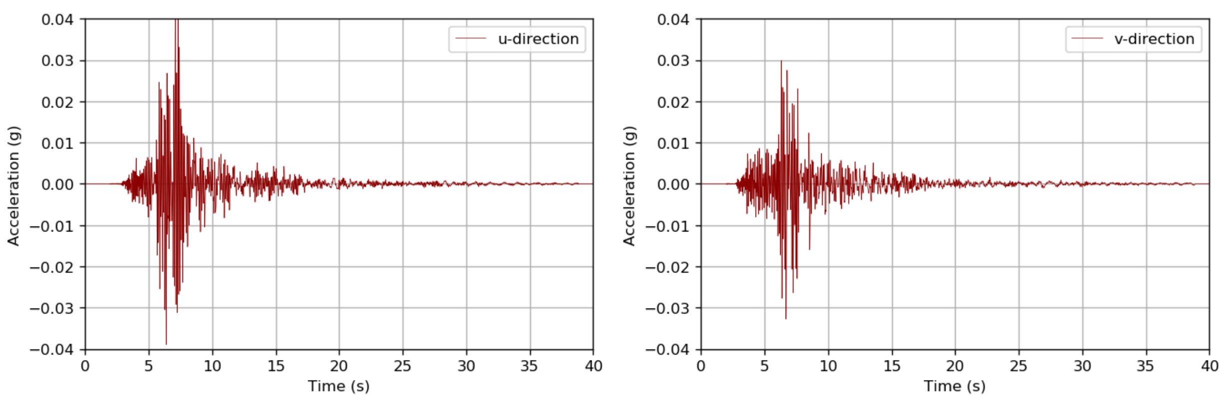


Figure 6. Time histories of input ground motion (Le-Teil earthquake)

The input ground motion for the seismic response analysis is the Le-Teil earthquake that occurred near the Cruas nuclear power plant in November 2019. This is an extremely rare case in which a significant seismic response was measured in a nuclear power plant with seismic isolation, and it was the impetus for the launch of the SMATCH benchmark program. Time histories of the input ground motion are shown in Figure 7.

Seismic response analysis is performed using Fast Nonlinear Analysis (FNA) available in SAP2000. Due to the complexity of the numerical model, it took about 3 hours to perform the modal analysis. The responses of the structure at three locations (EAU1~3) actually measured are provided through the benchmark program, and the seismic response analysis results are compared with the response of the same node as the sensor location.

COMPARISON OF IN-STRUCTURE RESPONSES TO THE LE-TEIL ERTHQUAKE

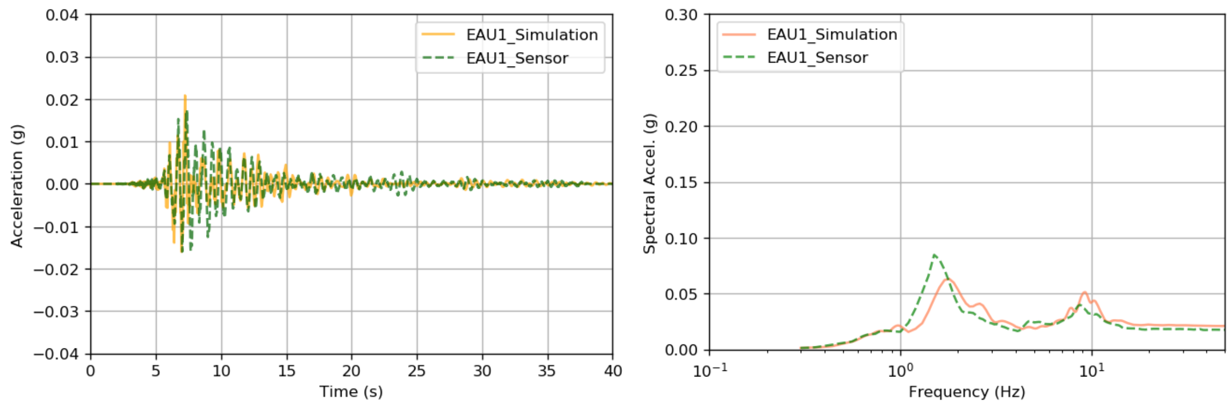


Figure 7. (a) Acceleration response and (b) in-structure response spectrum in y-direction at EAU1

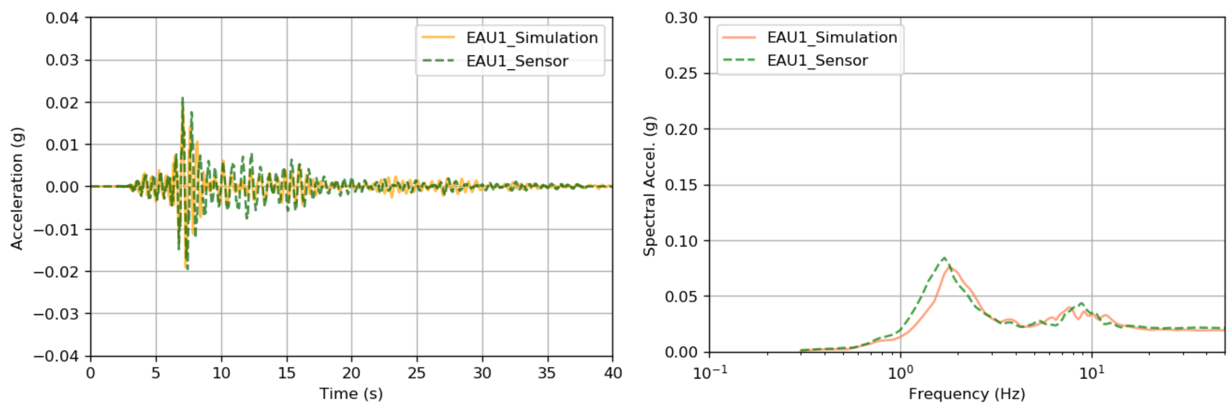


Figure 8. (a) Acceleration response and (b) in-structure response spectrum in x-direction at EAU1

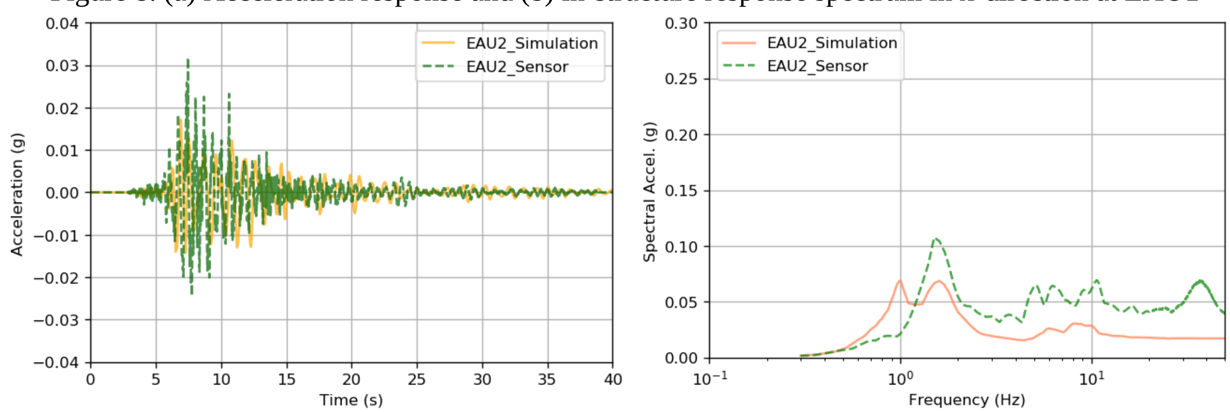


Figure 9. (a) Acceleration response and (b) in-structure response spectrum in y-direction at EAU2

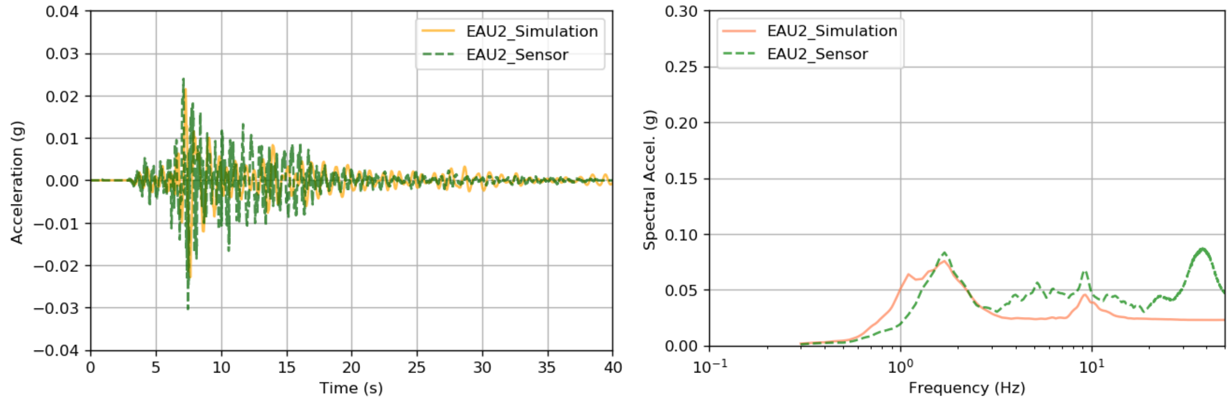


Figure 10. (a) Acceleration response and (b) in-structure response spectrum in x-direction at EAU2

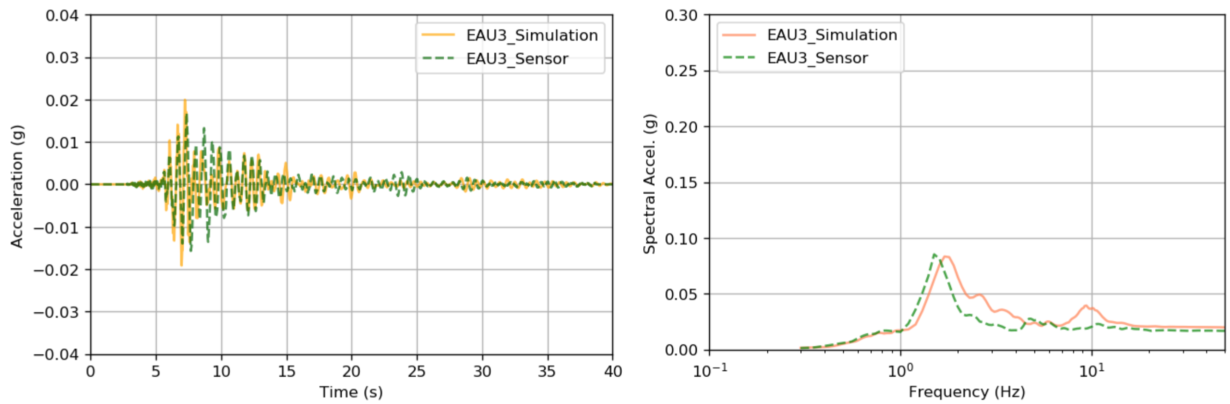


Figure 11. (a) Acceleration response and (b) in-structure response spectrum in y-direction at EAU3

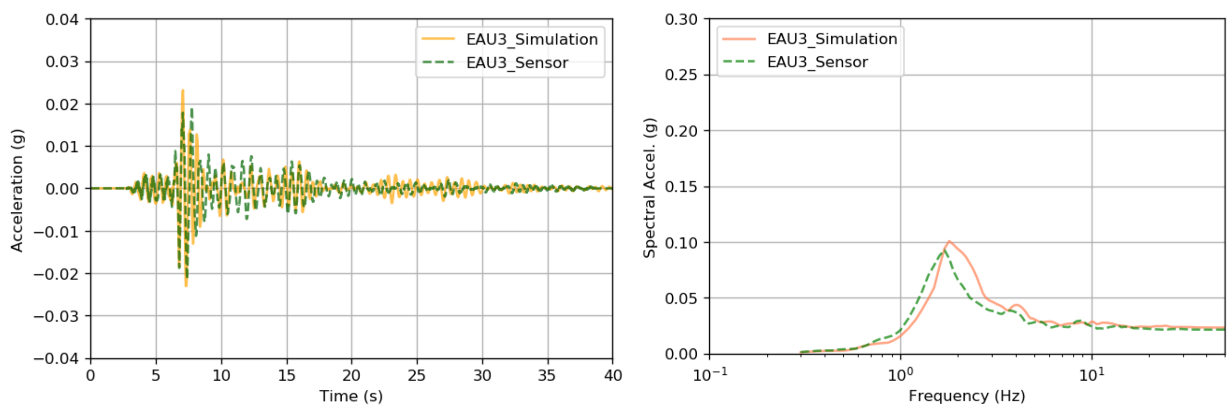


Figure 12. (a) Acceleration response and (b) in-structure response spectrum in x-direction at EAU3

The results of the seismic response analysis are compared with the responses at three points measured at nuclear power plant. The acceleration time history and the in-structure response spectrum for the two horizontal responses of the three nodes are compared. Two horizontal responses of the EAU1 are compared in Figures 7 and 8, the responses of the EAU2 are compared in Figures 9 and 10, and the responses of the EAU3 are compared in Figures 11 and 12.

The comparison results of the horizontal in-structure response spectrum (ISRS) of the structure show that the measured response and the simulation results are generally in good agreement. Because the sensors of

EAU1 and 3 are installed at the bottom of the structure and that the response of the seismic isolation mode is dominant, which leads to good agreement with the measured results. On the other hand, in the case of EAU2 located inside the structure, some differences appear to occur due to the influence of the response of the superstructure mode. In the process of converting the initial model developed on CODE-ASTER to the SAP2000 platform, the structural characteristics may not be accurately simulated due to differences in modelling (element and section definition, analysis methodology, etc.) between simulation programs.

CONCLUSION

In this study, we evaluate the seismic response of the base-isolated Cruas nuclear power plant as part of the SMATCH benchmark. Considering the aging of the seismic isolation devices installed in the 1980s, the seismic response is evaluated, and the overall trend is well matched with the measured response subjected to the Le-teil earthquake that occurred in 2019. It is estimated that some differences in the response are due to differences in the modelling of the structural characteristics of the superstructure. In the process of converting a very complex nuclear power plant numerical model to another analysis program platform, some modelling conversions may not have been perfectly performed, and it is expected that a more accurate evaluation will be possible once this issue addressed. This study, as part of the SMATCH benchmark, provides a valuable opportunity to evaluate the seismic response of an extremely rare base-isolated nuclear power plant and is expected to contribute to enhancing the seismic safety of nuclear power plants.

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