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Analytical study on building / ground nonlinear behaviors during earthquakes by Domain Reduction Method

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ABSTRACT

After the Great East Japan Earthquake in 2011, new regulatory standards were enforced in 2013 in Japan. Since then the safety requirements for nuclear reactor facilities have become more stringent. The magnitude of seismic input motion for design has considerably increased and building planning that can consider embedding effect has become indispensable. It is being essential to apply a design method with a higher degree of freedom that incorporates non-linearity between the building and the surrounding soil. The authors took particular note of the domain reduction method (DRM) shown in ASCE/SEI 4-16 in the previous paper, Nitta et al. (2019), and the validity of the DRM for the basemat uplift of the building with vertical incident was investigated. In this paper, the nonlinear behavior of an embedded reactor building during an earthquake is studied, focusing on the interaction between the underground outer wall and the surrounding soil, with a view to linking with a ground model of large area including the epicenter.

The finite difference method (FDM) is generally used to evaluate the wide area ground response during earthquakes. Since the generated ground response is limited to the long-period component, the response by the FDM is used in combination with the short-period component of the separately evaluated ground response. The input method to the DRM model of this synthesized wide area ground response was studied, and its validity was examined.

Continuity with design practice is a subject of great interest in the structural study considering the nonlinearity. First, from the viewpoint of consistency with past experimental results and theoretical solutions, the modelling method of the underground outer wall and the surrounding soil used in the building seismic response analysis was investigated. Subsequently, a seismic response analysis model of the embedded reactor building using DRM model was constructed, and the seismic response of the building focusing on the soundness of the underground outer wall was examined.

INTRODUCTION

After the Great East Japan Earthquake in 2011, new regulatory standards were enforced in 2013 in Japan. Since then the safety requirements for nuclear reactor facilities have become more stringent. The magnitude of seismic input motion for design has considerably increased and building planning that can consider embedding effect has become indispensable. It is being essential to apply a design method with a higher degree of freedom that incorporates non-linearity between the building and the surrounding soil. With this background, the authors took note of the domain reduction method (DRM), Bielak et.al. (2003), described in ASCE-4 in the previous studies and verified its validity for building earthquake responses considering the basemat uplift due to vertical incidence.

In this study, we perform seismic response analyses with a wide area ground model including an epicenter and examine nonlinear behaviors of an embedded reactor building during earthquakes, focusing on the interaction between the underground exterior wall and the surrounding soil.
At first the basemat uplift analysis due to contact and separation between the building and the ground are carried out, considering the nonlinearity of the building/ground. Then, the applicability of the DRM to the nonlinear behavior of the building/ground during earthquakes is investigated.

EVALUATION OF SOIL RESPONSE USING DRM MODEL

The concept of the DRM and the modeling method are shown in Figure 1. The DRM boundaries are formed as analytical energy transfer boundaries, where the response displacements of the wide area ground calculated separately are excited in the opposite direction. We modeled a three-dimensional region including a source fault for the wide area ground, performed Fourier transform both of the long-period response by the FDM and the short-period response by the stochastic Green's function method (SGF), and at the DRM boundaries input the synthesized waves applying cosine taper on those responses in the frequency domain

The frequency range for hybridization was determined considering the acceleration time history, the Fourier spectrum, and the acceleration response spectrum at the bedrock. The hybridization is schematically shown in Figure 2. The long-period waveforms at the DRM boundaries were directly obtained by the FDM. The short-period waveforms at the DRM boundaries were calculated in two steps. The first step was to compute the response on the bedrock by the SGF. The second step was to compute the response at the DRM boundaries by the complex response analysis of the two-dimensional FEM model. Finally, the long-period and the short-period waveforms were synthesized in the time domain.

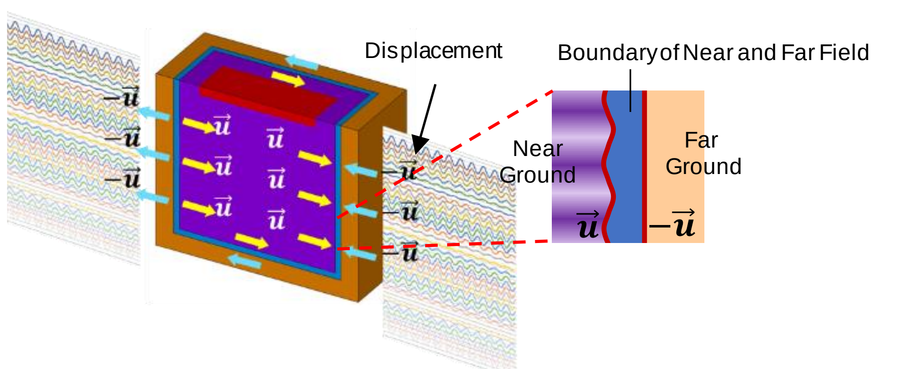


Figure 1. Concept of the DRM and the modeling method

WIDE-AREA GROUND RESPONSE

The long-period seismic motions using the three-dimensional FDM were computed by arranging a point source in a ground model consisting of three kinds of soil properties assuming excavated backfill (Soil I) on two layers of ground (Soil II and Rock III), as shown in Figure 2. The epicenter was placed at the depth of 20 km, 2.5 km away from the building. In the macroscopic parameters of the epicenter, a strike was set in the direction of the center of the building so that there would be no difference between the X and Y directions of the building, and a strike-slip fault with an inclination angle of 90° was considered. The microscopic parameters were set based on the idea, Irikura (2001), by assuming the point epicenter to be asperities without considering the background region. The source parameters and soil properties used are listed in Tables 1 and 2, respectively.

For the short-period waveforms using the SGF, a source equivalent to the FDM was used. The amount of stress drop was set large so that the response spectrum shows a peak in the frequency range band of about 5 to 10 Hz as shown in Table 1, which is the primary natural frequency of a typical nuclear building. The response results of the FDM and the SGF on the bedrock, and the waveforms and the acceleration response spectra of these combined waves are shown in Figs. 3 and 4, respectively. A cosine taper was applied to 1Hz to 2Hz to hybridize. The maximum acceleration values of the filtered long-period and short-period waveforms at G.L. -24.5 m, which is just below the building basemat were 400 gal and 1700 gal respectively. The acceleration response spectrum value around 10Hz, which is the primary natural frequency of the building, showed 4000 gal.

Table 1: Source parameters

Strike	Dip	Rake	Moment [N･m]	Stress Drop [MPa]
45°	90°	0°	4.5×10^{18}	144

Table 2: Soil properties

	Vs (m/s)	Vp (m/s)	ρ (t/m^3)	Q Value	Depth (m)
Soil I	300	1100	1.90	16.7	24.5
Soil II	1500	3000	2.40	16.7	373
Rock III	3400	6000	2.75	300	-

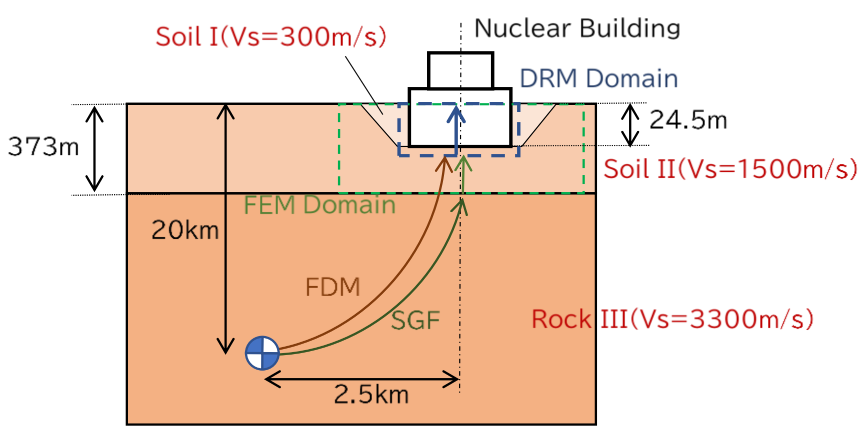


Figure 2. Wide-area ground model

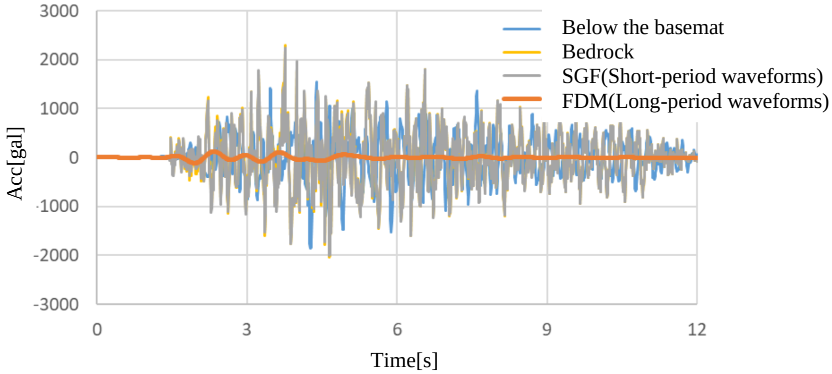


Figure 3. Time history waveform at bedrock and below the building basemat

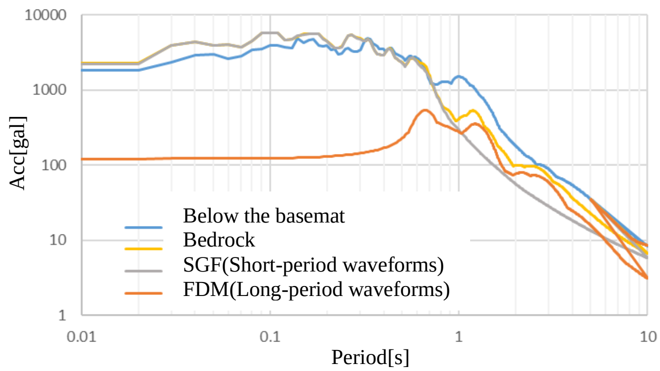


Figure 4. Acceleration response spectra at bedrock and below the building basemat

SOIL RESPONSE IN THE DRM REGION

The acceleration time histories obtained at the DRM boundaries were corrected using a linear function to remove drift of the displacement waveform. For soil damping, eigenvalue analysis of the ground was performed, and Rayleigh damping of 3% at the first and third order natural frequencies was given for Soil I. For Soil II, stiffness-proportional damping of 3% in the third order natural frequency was used. Figure 5 shows the comparison of the maximum acceleration response values in the depth direction for the FDM, 2D-FEM and the DRM. Since the epicenter depth was 20 km, it was considered that the input motion from the lower end of the region was mostly vertical incident. So, it was possible to compare those of FEM and DRM because of the same incident conditions.

The amplification trend from the bottom of the model to the soil surface are generally consistent, and the difference between the two is within about 10% at the bottom of the basemat and the soil surface, confirming that the acceleration responses by the DRM showed the reasonable.

Figure 6 shows the comparison of the maximum acceleration contours of the DRM and 2D-FEM. It was confirmed that the maximum values were found at the soil surface in the center of both models, and that the values were similar to around 4500 gal. However, some large responses occurred locally at the soil surface only in the DRM, the cause of which will be investigated in the future. It was confirmed that the response shows mostly good agreement.

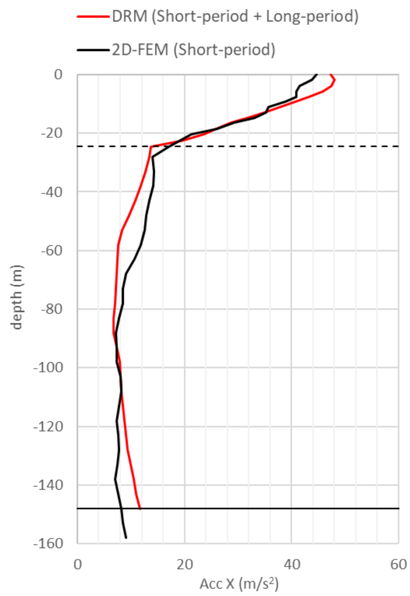
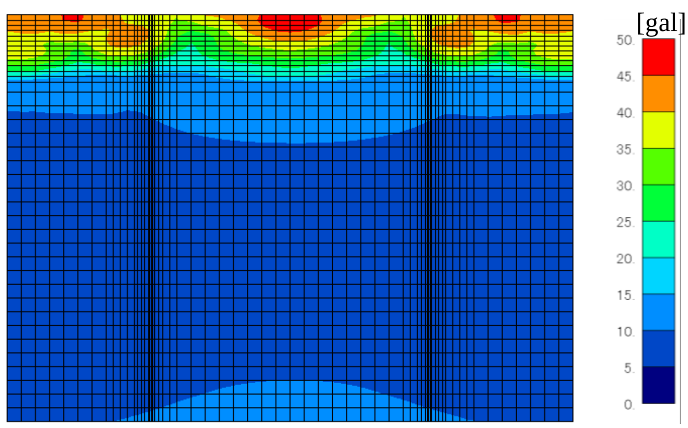
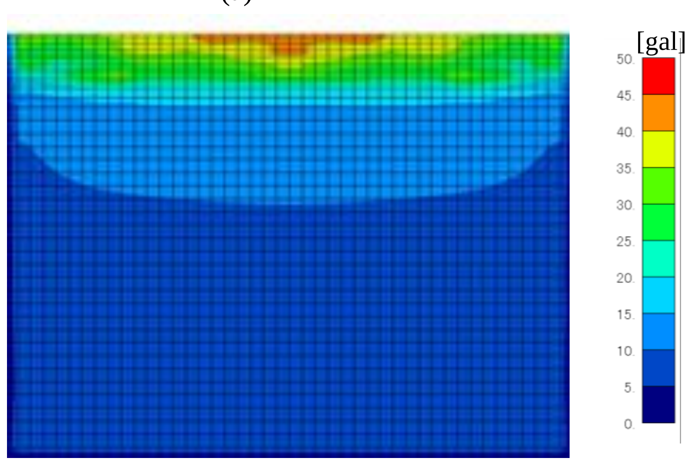


Figure 5. Comparison of the maximum acceleration response values



(a) DRM



(b) FEM

Figure 6. Comparison of the maximum acceleration contours

RESPONSE ANALYSIS METHOD OF SOIL-STRUCTURE SYSTEM

The analysis model was based on the DRM model of the two-layer ground structure of Soil I and Soil II created in the previous section. The embedded building was setup to take into account the soil-structure interaction shown in Figure 7. The building had a basemat of 100 m in the NS direction × 70 m in the EW direction and the depth of embedment was assumed to be 24.5m.

A half model was adopted for the direction of excitation (X: NS direction), and the modeling area was 2 times the width of the building based on the knowledge of the analysis of the DRM model previously reported, while 5 times the width of the building is recommended by JEAC (2008).

The building was a standard PWR reactor building with reference to JEAG (1987) and was modeled as a three-stick model with mass and beam elements as shown in Figure 1. Three sticks are composed of the Prestressed Concrete Containment Vessel (PCCV), the Concrete Internal Structure (I/C) and the Reactor External Building (REB). The restoring force characteristics were set for the seismic walls. The outer wall of the REB, which is connected to the soil, was modeled with solid elements. The nonlinearity against cracking of reinforced concrete material was considered based on Maekawa (2003), and the nonlinearity against out-of-plane deformation due to earth pressure was considered. The REB stick model was pin jointed to the outer wall with rigid rods assuming to be a rigid floor.

Contact elements that allow consideration of contact, separation, and slip were placed between the outer walls of the building and Soil I, and joint elements that allow consideration of the basemat uplift were placed between the bottom of the basemat and Soil II.

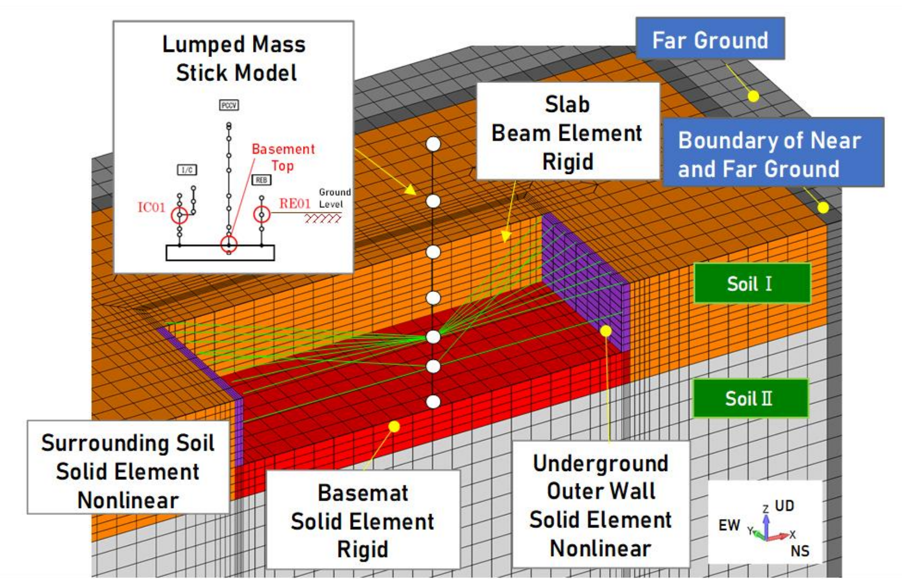


Figure 7. Analysis model of soil-structure interaction

The material nonlinearity of the oil around the building was modeled using the Mohr Coulomb model to account for shear failure of the soil. In order to determine the range in which the nonlinearity of the soil was taken into consideration, pushover analysis was carried out by applying the inertial force of the building statically. The region considering nonlinearity was set as shown in Figure 8, taking into account the slip surface assumed from the shear strain distribution shown in Figure 9 and the passive slip surface ([45-φ/2] equals 30 degrees) obtained from the internal friction angle φ (30 degrees) of Soil II.

The input to the DRM model boundaries was a hybrid of the long-period response wave from the FDM discussed in the previous section and the short-period response wave from the SGF.

The damping of each building portion was assumed to be the stiffness-proportional damping (C=βK) due to the material damping of each member with respect to the dominant frequencies of the PCCV, the I/C, and the REB.

The joint elements between the building and the soil were set to small stiffness-proportional damping values in order to be numerically stable. The DRM model was analyzed using the Domain Decomposition Method (DDM), Mandel (1993), in parallel computing. Time history nonlinear response analysis was performed by computing interval DT=0.001s and duration time Tmax=12.0s.

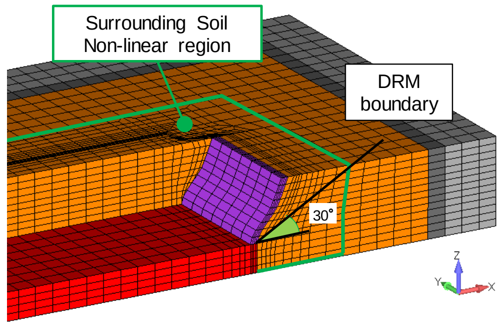


Figure 8. Surrounding soil region considering nonlinearity

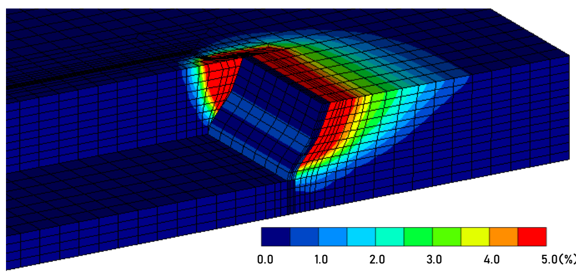


Figure 9. Maximum shear strain distribution

RESPONSES OF SURROUNDING SOIL AND BASEMENT EXTERIOR WALL

As a response analysis of the soil, the comparison was made between the soil-only model without a building and the coupled building-soil model in Part 1. The maximum acceleration distribution of the entire model is shown in Figure 10. There showed roughly good correspondence between the two models for the maximum acceleration of the far ground. For the maximum acceleration response, the response of the basemat bottom surface was slightly reduced compared with the soil-only model due to the embedment effect where the soil was excavated at the building position. For the sides of the building, the maximum acceleration was larger due to the effect of contact and separation with the soil.

The maximum shear strain distribution of the soil around the building is shown in Figure 11. Theoretical passive earth pressure values and shearing stress-strain relationships for the failure of the soil by the stand-alone analytical model are also included for reference. The maximum deformation and the out-of-plane shear stress distribution of the exterior wall are shown in Figure 12. The soil around the building was subjected to shear failure, resulting in strains larger than 1%. The out-of-plane shear stress of the exterior wall in contact with the soil was about 1.5 N/mm^2 due to the reduction in strength caused by the soil failure and no shear failure in the exterior walls occurred.

The deformation of the exterior wall in contact with the soil was restrained at the floor level where the rigid bars are pin connected to the REB. The walls between the floors showed out-of-plane deformation, with out-of-plane shear stress of about 3 N/mm^2 at the floor level and at the bottom of the exterior wall, resulting in shear failure.

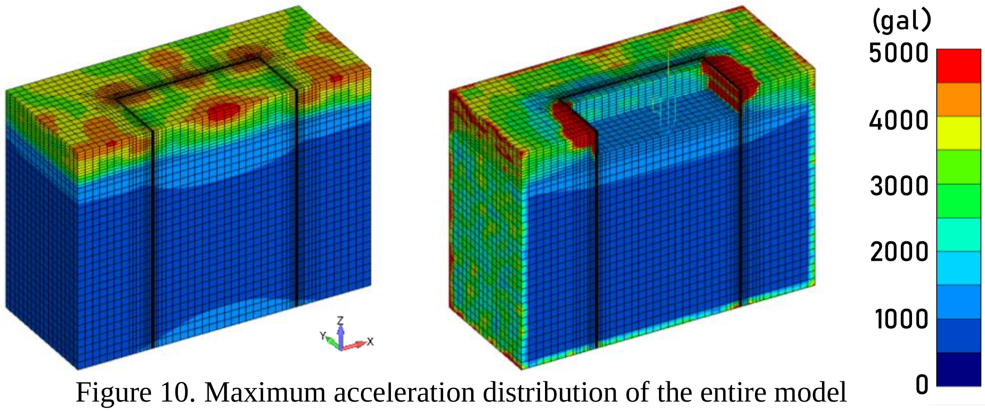


Figure 10. Maximum acceleration distribution of the entire model

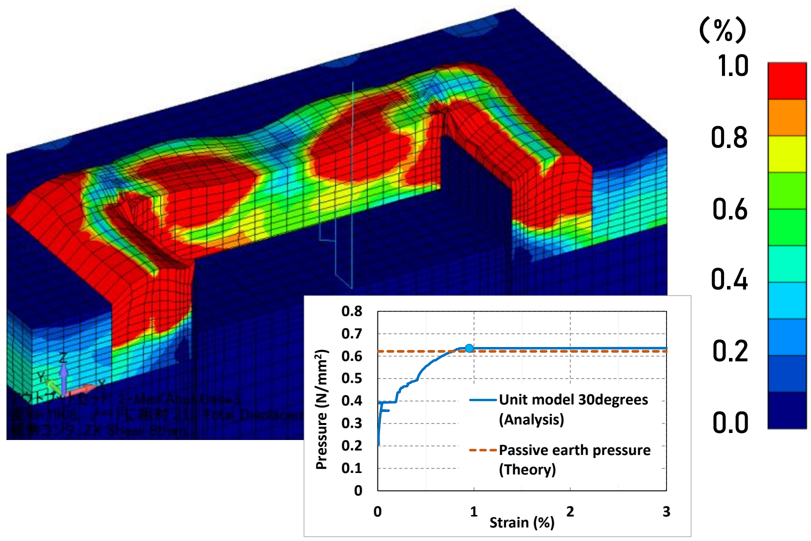


Figure 11. Maximum shear strain distribution in the soil around the building

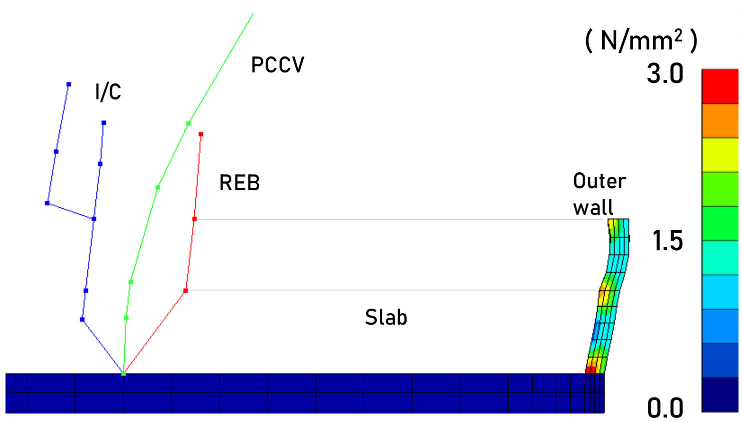


Figure 12. Maximum deformation of the building and out-of-plane shear stress distribution of the exterior wall

INFLUENCE OF EMBEDMENT EFFECT ON BUILDING RESPONSE PROPERTIES

The acceleration response spectra (FRS) of the top of the basemat, the REB, and the I/C of the mass building are shown in Figure 13. A sensitivity analysis with no connection between the exterior wall and the side soil was performed. The comparison showed with the case where the interaction with the soil acts only between the bottom of the basemat and the soil.

The response at the top of the basemat was almost same for both cases. The I/C, with no direct connection to the surrounding soil, had the same predominant period, but the REB response, which interacts with the soil through the exterior wall, showed fluctuations in the predominant period.

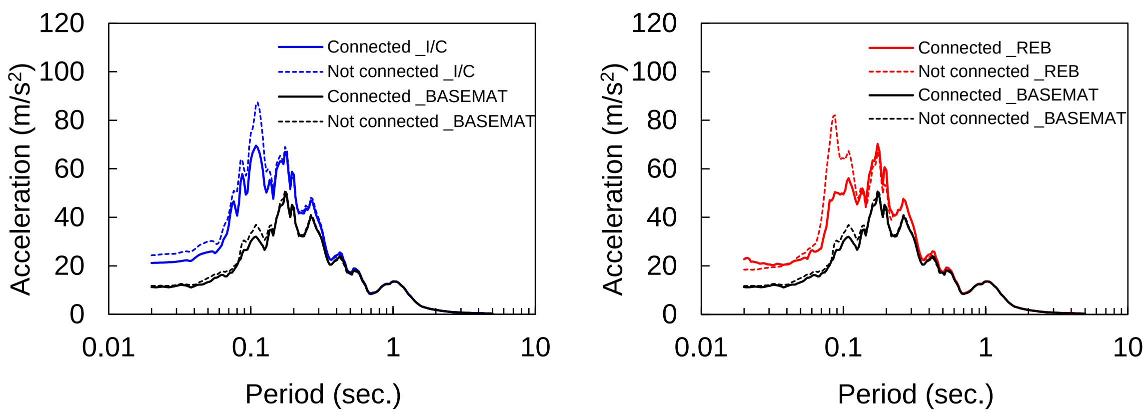


Figure 13. FRS of the top of the basemat, REB, and I/C (h=5%)

CONCLUSIONS

Assuming a point source in the wide ground area and synthesizing the separately calculated time histories of short-period and long-period waves, the response analysis of the DRM region was conducted, and the following findings were obtained.

It was confirmed that there was no significant difference between the response in the DRM region and that in the two-dimensional ground FEM region.

However, some large responses occurred locally at the soil surface only in the DRM, the cause of which will be investigated in the future.
basemat uplift analyses considering the material non-linearity of the building / ground and the contact and separation between the building and the soil using the DRM model were conducted.

REFERENCES

Bielak, J., Loukakis, K., Hisada, Y., and Yoshimura C. (2003). “Domain Reduction Method for Three-Dimensional Earthquake Modeling in Localized Regions, Part I & II,” *Bulletin of the Seismological Society of America*, Vol. 93, No.2, pp. 817-840.

Irikura, K. and Miyake, H. (2001). “Strong Ground Motion Prediction for scenario earthquake (in Japanese)”, *Journal of Geography*, Vol. 110, pp. 849-875.

Maekawa, K., Pimanmas, A. and Okamura, H. (2003). “Nonlinear Mechanics of Reinforced Concrete,” *Spon Press*, London, 2003.

Mandel, J. (1993). “Balancing domain decomposition,” *Communications on Numerical Methods in Engineering*, Vol. 9, pp.233-241.

Nitta, Y., Hayashi, K., Matsumoto, M., Akimoto, M. and Ogata, T. (2019). “A Feasibility Study on Domain Reduction Method for Non-linear Seismic Response Analysis of Soil-Structure Interaction System,” *SMiRT-25*, Charlotte, North Carolina, USA, 2019, Division III.

The Japan Electric Association. (1987). *Technical Guidelines for Aseismic Design of Nuclear Power Plants (JEAG4601-1987)* (in Japanese).

The Japan Electric Association. (2008). *Technical Code for Seismic Design of Nuclear Power Plants (JEAC 4601-2008)* (in Japanese).