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EARTHQUAKE RESPONSE ANALYSIS OF A SEISMICALLY ISOLATED CONTAINMENT BUILDINGS IN NUCLEAR POWER PLANTS CONSIDERING SOIL-STRUCTURE INTERACTIONS

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ABSTRACT

Earthquake response analyses of seismically isolated containment buildings in nuclear power plants are carried out by considering soil-structure interactions, and then the effects of seismic isolation are investigated. The structure and near-field soil are modeled by finite element method while far-field soil by consistent transmitting boundary. The equation of motion of a soil-structure interaction system under incident seismic wave is described. The described equations of motion are solved to carry out response analysis of a seismically isolated soil-structure system. Generally, the results of this analysis show that seismic isolation significantly reduces the relative responses of the structures. However, if the natural frequency of the soil is similar to that of the seismically isolated structure, the responses of the containment buildings rather increase due to interactions in the system. Therefore, the seismic isolation devices must be carefully applied to structures on a flexible soil after performing precise analysis of the soil-isolator-structure system to verify the stability.

INTRODUCTION

Accidents in nuclear power plants have brought about terrible results such as large casualties, property damages, and semi-permanent radiation contamination, as we have seen from disasters at Three Mile Island in 1979, Chernobyl in 1986, and Fukushima in 2011. Nuclear power plants, therefore, require much more strict safety conditions than other structures. This requirement also applies to nuclear power plants in the case of earthquakes. In particular, containment buildings in nuclear power plants must be able to prevent leakage of radioactive materials in the event of earthquakes. Since the thickness of external walls in the containment building should be large enough to prevent the leakage, the stiffness of the buildings is also quite large. Containment buildings with high stiffness have short natural periods. When a structure with a short natural period is constructed on a flexible soil, its responses are significantly amplified due to soil-structure interactions. When structural safety of containment buildings in nuclear power plants is evaluated, therefore, dynamic analysis must be carried out considering soil-structure interactions. Recently, U.S. Nuclear Regulatory Commission (2007) reinforced regulations so that soil-structure interactions must be considered when the velocity of shear wave is less than 2,440 m/sec.

Various methods have been applied to secure seismic safety of structures constructed in regions that are ripe for a massive earthquake: design to secure enough strength against expected earthquakes in the regions, vibration control to prevent structures from severely deforming, damping devices to absorb the bulk of external energy, and seismic isolation to isolate structures from the ground so that vibration of ground is not directly transferred to them, etc. Generally, these methods have not been used alone, but several methods have been combined to use. Seismic isolation devices have been applied to nuclear power plants in France, South Africa, and Japan. Recently, concerns about application of seismic isolation devices to nuclear power plants have been increased and many researches on this subject have been actively made in the USA and Japan. As such, seismic isolation devices have been provided to secure seismic safety of containment buildings in nuclear power plants in high seismic regions. To apply these devices, however, it is required to investigate the effects of soil-structure interactions that affect the dynamic behaviors of seismic isolated containment buildings in nuclear power plants.

Several researchers have performed researches on the dynamic characteristics of seismically isolated soil-structure systems. Novak & Henderson (1989) and Tongaonkar & Jangid (2003) verified that soil-structure interactions should be considered for analysis of seismically isolated structures when the stiffness of soil was less than 10 times of seismic isolation devices. Tsai et al. (2004) verified that flexibility and radiation damping should be strictly considered to accurately evaluate the seismic responses of structures built on friction pendulums. Cho et al. (2004) carried out seismic response analysis of seismically isolated liquid storage tanks considering fluid-structure-soil interactions and then verified that soil-structure interactions increased the dynamic responses of structures. Spyrakos et al. (2009) proved the effect that soil-structure interactions affected the natural modes of seismically isolated structures, using a simple dynamic model.

In this study, we carry out dynamic analysis on seismically isolated containment buildings in nuclear power plants to verify the effects of seismic isolation, strictly considering soil-structure interactions. First of all, general analysis methods of soil-structure interactions are explained, and then a numerical example and concrete analysis methods of the soil and structures applied to this study are explained. Using these analysis methods, response history analysis of containment buildings in nuclear power plants is carried out to verify how soil-structure interactions affect dynamic behaviors of these buildings.

Low-frequency contents of a ground motion can significantly amplify responses, such as internal forces and drift, of the isolated structure because the fundamental frequency of the non-isolated structure is shifted down by applying isolators. The frequency contents of the ground motions depend on the bedrock motion and the property of soil underneath the containment buildings. In order to investigate on the effect of soil property on the response of the isolated containment building, this study performs several numerical analyses on the seismically isolated containment buildings built on different soils considering soil-isolator-structure interaction. The benefit of applying isolators to the containment building is evaluated.

ANALYSIS METHODS FOR SOIL-STRUCTURE INTERACTIONS

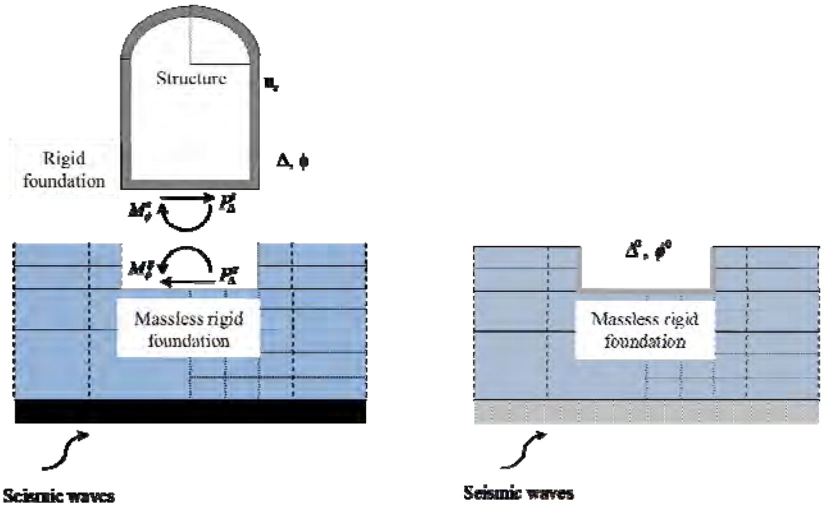
The soil is divided into two parts: a near-field and a far-field where extends to the infinite. For the near-field where structures and geometric shapes of soils are irregular and nonlinear behaviors are expected, numerical models are constructed using finite elements; and for the far-field where geometric shapes and material properties of soils are uniform in the horizontal direction and linear behaviors are expected, numerical models are constructed using methods that energy radiation to the infinite is exactly considered. Typical numerical models for the far-field include consistent transmitting boundary (Kausel, 1974; Lee & Tassoulas, 2011; Lee et al., 2012), boundary elements (Beskos, 1987 & 1997), infinite elements (Astley, 2000) and absorption boundary conditions (Givoli, 2004), etc. Consistent transmitting boundary is an appropriate model for representing layer structures of the soil, since it uses analytic solutions in the horizontal direction that extends to the infinite and uses discrete solutions in the vertical direction using the concept of finite elements. In this study, therefore, we constructed numerical models for the far-field using consistent transmitting boundary.

General Analysis Method

The soil-structure system can be divided into two parts as in Fig. 1(a). Then, there are interactions between a structure and a massless rigid foundation. In the soil-structure system, generally, there are interactions that correspond to the 6 degrees of freedom of the massless rigid foundation. Assuming that containment buildings in nuclear power plants basically have axis-symmetric shape, however, effects of one-axis horizontal motion of the soil are considered: interactions of translational displacement Δ in the horizontal direction and rotational displacement about the other horizontal perpendicular direction are considered. Let interactions on the structure be P^s_Δ and M^s_ϕ that correspond to the displacements Δ and ϕ, respectively. Then, the following equation of motion can be formulated for the structure:

$$\begin{bmatrix} \mathbf{S}_{ss} & \mathbf{S}_{s\Delta} & \mathbf{S}_{s\phi} \\ \mathbf{S}_{\Delta s} & S_{\Delta\Delta} & S_{\Delta\phi} \\ \mathbf{S}_{\phi s} & S_{\phi\Delta} & S_{\phi\phi} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_s \\ \Delta \\ \phi \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ P^s_\Delta \\ M^s_\phi \end{Bmatrix} \tag{1}$$

where $\mathbf{S}_{ss}$, $\mathbf{S}_{si} = \mathbf{S}^T_{is}$, and $S_{ij} = S_{ji}$ $(i, j = \Delta, \phi)$ are the dynamic stiffness of the structure.



(a) (b)

Figure 1. Soil-structure interaction system: (a) soil and structure and (b) soil without structure

Next, suppose a structure system, as shown in Fig. 1(b), which has only a massless rigid foundation without a structure. When seismic wave reaches this structure system, it generates the dynamic responses of the foundation; translational displacement Δ^0 and rotational displacement ϕ^0. Then, force acting on the foundation is zero since there is no structure. If a structure is placed on the foundation, then it generates soil-structure interactions. The interactions P^g_Δ and M^g_ϕ act on the foundation and the responses of the foundation is those of Δ and ϕ rather than Δ^0 and ϕ^0. Therefore, the relationship between the interactions acting on the foundation and the responses can be represented by this:

$$\begin{Bmatrix} P^g_\Delta \\ M^g_\phi \end{Bmatrix} = \begin{bmatrix} S^g_{\Delta\Delta} & S^g_{\Delta\phi} \\ S^g_{\phi\Delta} & S^g_{\phi\phi} \end{bmatrix} \begin{Bmatrix} \Delta - \Delta^0 \\ \phi - \phi^0 \end{Bmatrix} \tag{2}$$

where $S_{ij}^{g} = S_{ji}^{g}$ $(i, j = \Delta, \phi)$ is the dynamic stiffness of the massless rigid foundation. For interactions acting on the structure, $P_{\Delta}^{s} = -P_{\Delta}^{g}$ and $M_{\phi}^{s} = -M_{\phi}^{g}$. Then, the following equation of motion can be finally obtained from Eq. (1) and Eq. (2):

$$\begin{bmatrix} \mathbf{S}_{ss} & \mathbf{S}_{s\Delta} & \mathbf{S}_{s\phi} \\ \mathbf{S}_{\Delta s} & S_{\Delta\Delta} + S_{\Delta\Delta}^{g} & S_{\Delta\phi} + S_{\Delta\phi}^{g} \\ \mathbf{S}_{\phi s} & S_{\phi\Delta} + S_{\phi\Delta}^{g} & S_{\phi\phi} + S_{\phi\phi}^{g} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_{s} \\ \Delta \\ \phi \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ S_{\Delta\Delta}^{g}\Delta^{0} + S_{\Delta\phi}^{g}\phi^{0} \\ S_{\phi\Delta}^{g}\Delta^{0} + S_{\phi\phi}^{g}\phi^{0} \end{Bmatrix} \tag{3}$$

To carry out analysis of soil-structure interactions from Eq. (3), (i) dynamic stiffness of the massless rigid foundation and (ii) the response of the massless rigid foundation due to the incident seismic wave should be estimated when there is no structure.

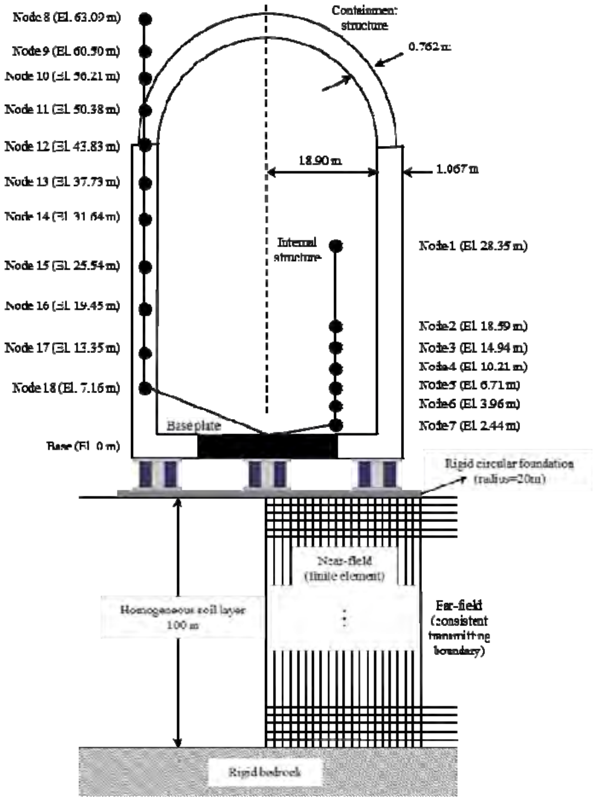


Figure 2. Numerical example of the seismically isolated containment building in NPP

Dynamic Stiffness of Seismic Isolated Containment Buildings

Among components in Eq. (3), we now explain the numerical model of containment buildings in nuclear power plants. Fig. 2 shows a seismically isolated containment building and an idealized structure system. A numerical model of containment buildings is constructed with Timoshenko beam elements considering shear deformation. Stiffness matrix is given by Eq. (4):

$$\begin{bmatrix} \frac{12EI}{L^3}\frac{1}{1+12\beta} & \frac{6EI}{L^2}\frac{1}{1+12\beta} & -\frac{12EI}{L^3}\frac{1}{1+12\beta} & \frac{6EI}{L^2}\frac{1}{1+12\beta} \\ \frac{6EI}{L^2}\frac{1}{1+12\beta} & \frac{4EI}{L}\frac{1+3\beta}{1+12\beta} & -\frac{6EI}{L^2}\frac{1}{1+12\beta} & \frac{2EI}{L}\frac{1-6\beta}{1+12\beta} \\ -\frac{12EI}{L^3}\frac{1}{1+12\beta} & -\frac{6EI}{L^2}\frac{1}{1+12\beta} & \frac{12EI}{L^3}\frac{1}{1+12\beta} & -\frac{6EI}{L^2}\frac{1}{1+12\beta} \\ \frac{6EI}{L^2}\frac{1}{1+12\beta} & \frac{2EI}{L}\frac{1-6\beta}{1+12\beta} & -\frac{6EI}{L^2}\frac{1}{1+12\beta} & \frac{4EI}{L}\frac{1+3\beta}{1+12\beta} \end{bmatrix} \tag{4}$$

where E is Young's modulus of element, A is cross section, I is the second moment of cross-section area, L is the length, $\beta = EI/(GA_sL^2)$, G is shear modulus, and A_s is total cross-section area. Lumped masses are used to build mass matrix of the containment building. The rotational inertia of the structure is neglected.

Seismic isolation devices are simply idealized using springs and dampers. Spring and damper constants of seismic isolation devices are $k_b = (M + m_b)\omega_b^2$, $c_b = 2(M + m_b)\omega_b\xi_b$, respectively (Chopra, 2012). If the upper structure is assumed to be rigid, $\omega_b = 2\pi f_b$ and ξ_b are the natural frequency and damping ratio of the seismic isolation system; M and m_b are masses of the upper structure and base plate, respectively; and f_b and ξ_b are the natural frequency and damping ratio of seismic isolation devices.

Dynamic Stiffness and Input Motion of a Massless Rigid Foundation

As it can be seen in Eq. (3), dynamic stiffness and input motion of a massless rigid foundation should be estimated to analyze soil-structure interactions. To do this, the responses of the foundation by incident seismic wave are evaluated when there is only a foundation without a structure as shown in Fig. 1(b) (Wolf, 1985). For the near-field where the massless rigid foundation is placed, numerical models were constructed using finite elements; and for the far-field, numerical models were constructed using consistent transmitting boundary (Kausel, 1974; Lee & Tassoulas, 2011; Lee et al., 2012). Analysis methods of soil-structure interactions for incident wave using consistent transmitting boundary as well as its formulation should conform to methods in Kausel (1974) and Lee et al. (2012).

When there is only a masselss rigid foundation without a structure, equation of motion can be represented by Eq. (5) (Lee et al., 2012):

$$\begin{bmatrix} S^n_{\Delta\Delta} & S^n_{\Delta\phi} & \mathbf{S}^n_{\Delta n} & \mathbf{S}^n_{\Delta f} \\ S^n_{\phi\Delta} & S^n_{\phi\phi} & \mathbf{S}^n_{\phi n} & \mathbf{S}^n_{\phi f} \\ \mathbf{S}^n_{n\Delta} & \mathbf{S}^n_{n\phi} & \mathbf{S}^n_{nn} & \mathbf{S}^n_{nf} \\ \mathbf{S}^n_{f\Delta} & \mathbf{S}^n_{f\phi} & \mathbf{S}^n_{fn} & \mathbf{S}^n_{ff} + \mathbf{R}^f_{ff} \end{bmatrix} \begin{Bmatrix} \Delta^0 \\ \phi^0 \\ \mathbf{U}_n \\ \mathbf{U}_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ \mathbf{0} \\ \mathbf{R}^f_{ff}\mathbf{U}^\star_f - \mathbf{P}^\star_f \end{Bmatrix} \tag{5}$$

where the subscript n is the degree of freedom that is not on the foundation and consistent transmitting boundary but pertains to the near-field, the subscript f is the degree of freedom that pertains to consistent transmitting boundary. The superscript n means the near-field of the soil, and the superscript f means the far-field. In Eq. (5), therefore, $\mathbf{S}^n_{ij} = (\mathbf{S}^n_{ji})^T$ ($i, j = \Delta, \phi, n, f$) is the dynamic stiffness of the near-field constructed by finite elements, $\mathbf{R}^f_{ff}$ is the dynamic stiffness of the far-field obtained from consistent transmitting boundary. $\mathbf{U}^\star_f$ and $\mathbf{P}^\star_f$ are displacement on the free field ground by incident seismic wave and equivalent nodal force generated on the boundary between the near-field and the far-field in Fig. 2, respectively. When matrix condensation is made with keeping the degrees of freedom of the foundation Δ^0 and ϕ^0 only, the dynamic stiffness and input motion of the foundation can be obtained as in Eq. (6a) and Eq. (6b), which are entered in Eq. (3) to carry out analysis of soil-structure interactions.

$$\begin{bmatrix} S^g_{\Delta\Delta} & S^g_{\Delta\phi} \\ S^g_{\phi\Delta} & S^g_{\phi\phi} \end{bmatrix} = \begin{bmatrix} S^n_{\Delta\Delta} & S^n_{\Delta\phi} \\ S^n_{\phi\Delta} & S^n_{\phi\phi} \end{bmatrix} - \begin{bmatrix} \mathbf{S}^n_{\Delta n} & \mathbf{S}^n_{\Delta f} \\ \mathbf{S}^n_{\phi n} & \mathbf{S}^n_{\phi f} \end{bmatrix} \begin{bmatrix} \mathbf{S}^n_{nn} & \mathbf{S}^n_{nf} \\ \mathbf{S}^n_{fn} & \mathbf{S}^n_{ff} + \mathbf{R}^f_{ff} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{S}^n_{n\Delta} & \mathbf{S}^n_{n\phi} \\ \mathbf{S}^n_{f\Delta} & \mathbf{S}^n_{f\phi} \end{bmatrix} \tag{6a}$$

$$\begin{Bmatrix} \Delta^0 \\ \phi^0 \end{Bmatrix} = -\begin{bmatrix} S^g_{\Delta\Delta} & S^g_{\Delta\phi} \\ S^g_{\phi\Delta} & S^g_{\phi\phi} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{S}^n_{\Delta n} & \mathbf{S}^n_{\Delta f} \\ \mathbf{S}^n_{\phi n} & \mathbf{S}^n_{\phi f} \end{bmatrix} \begin{bmatrix} \mathbf{S}^n_{nn} & \mathbf{S}^n_{nf} \\ \mathbf{S}^n_{fn} & \mathbf{S}^n_{ff} + \mathbf{R}^f_{ff} \end{bmatrix}^{-1} \begin{Bmatrix} \mathbf{0} \\ \mathbf{R}^f_{ff}\mathbf{U}^*_f - \mathbf{P}^*_f \end{Bmatrix} \tag{6b}$$

NUMERICAL EXAMPLE

Using the analysis methods mentioned above, seismic analysis of a seismically isolated containment building in Fig. 2 is carried out in consideration of soil-structure interactions. In the structure, elastic modulus of concrete is 33.049 GPa; Poisson ratio is 0.2778; equivalent viscous damping ratio of hysteretic damping is 2%; information on nodal masses and elements of the structure is shown in Table 1; mass of the base plate is 9020.6 ton; and its rotational inertia is $885.18 \times 10^6\ kg \cdot m^2$. It is also assumed that the natural frequency of seismic isolation devices is $f_b = 0.5\,\text{Hz}$, and damping ratio $\xi_b = 10\%$.

Table 1: Node masses and element descriptions of the NPP containment building

node	mass (ton)	element	area (m^2)	shear area (m^2)	2^{nd} moment of area (m^4)
internal structure					
1	372.0	2 to 1	17.7	6.5	34.5
2	553.4	3 to 2	72.5	33.4	1726.2
3	3873.7	4 to 3	161.7	55.7	7767.9
4	1705.5	5 to 4	182.1	67.8	11220.3
5	2853.1	6 to 5	205.3	135.6	10357.2
6	1138.5	7 to 6	237.8	144.9	10357.2
7	1260.1	Base to 7	185.8	122.6	9494.1
containment structure					
8	86.2	9 to 8	92.0	46.5	1726.2
9	961.6	10 to 9	92.0	46.5	6904.8
10	1120.4	11 to 10	92.0	46.5	12946.5
11	1369.9	12 to 11	92.0	46.5	16398.9
12	2091.1	13 to 12	130.1	65.0	24166.7
13	1905.1	14 to 13	130.1	65.0	24166.7
14	1905.1	15 to 14	130.1	65.0	24166.7
15	1905.1	16 to 15	130.1	65.0	24166.7
16	1905.1	17 to 16	130.1	65.0	24166.7
17	1905.1	18 to 17	130.1	65.0	24166.7
18	2086.6	Base to 18	130.1	65.0	24166.7

It is assumed that the seismically isolated containment building is located on the surface of the ground by a circular rigid foundation with its radius $R_f = 20\,\text{m}$: embedment effects are neglected. When embedment effects are considered, seismic analysis can be performed in the same way (Lee et al., 2012). It is assumed that the density of the soil ρ_s is $2000\,\text{kg}/\text{m}^3$; Poisson ratio 0.333; equivalent viscous damping ratio of hysteretic damping 5%; and the homogeneous soil depth to rigid bedrock $H_s = 100\,\text{m}$. Varying the shear wave velocity C_S of the homogeneous soil to 2000 m/sec, 1000 m/sec, 500 m/sec, and

200 m/sec, the effects of flexibility of the soil are investigated. The natural frequency of the soil for each shear wave velocity is 5 Hz, 2.5 Hz, 1.25 Hz, and 0.5 Hz, respectively.

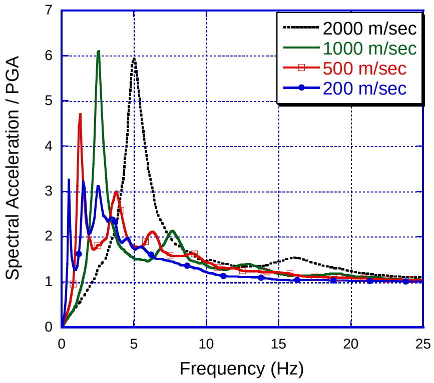


Figure 3. Average of 5% damped response spectrums of foundation input motions

In this example, vertical incident SH wave is only considered. Methods in this study, however, can be applied to general seismic wave with arbitrary incident angle (Lee et al., 2012). Control motion to be applied to bedrock can be defined as $u_{outcrop}$ that is defined for outcrop of bedrock. In this study, the motions of the bedrock are generated by SIMQKE (Gasparini & Vanmarcke, 1976), according to the response spectrum of Reg. Guide 1.60 (USNRC, 1973). Motions of the bedrock having the shaking duration equivalent to the earthquake of magnitude 7.0-7.5, 6.5-7.0, 6.0-6.5, 6.0-5.5, and 5.0-5.5 are generated respectively, where the envelope function of the ground acceleration is used for each magnitude of earthquake (ASCE, 2000). 10 motions of the bedrock are generated for each magnitude of earthquake and applied to the example soil-isolator-structure system. The average of 5% damping response spectrums of foundation input motions, which is normalized with respect to PGA, due to the 10 bedrock motions are plotted in Fig. 3.

In cases of a rigid soil (neglecting soil-structure interaction) and non-rigid soils (having different shear-wave velocities), seismic responses of structures are evaluated for both seismically isolated containment buildings and non-isolated ones. Firstly, the changes of the relative responses of the structure depending on variation in stiffness of the soil are investigated when the control motion is magnitude 7.0-7.5. Examples of relative displacement histories of the top part with respect to the base plate of the containment building are plotted in Fig. 4. We can see that the seismic isolation of the containment building efficiently reduces seismic responses except for the case of shear-wave velocity 200 m/sec as shown in the figure. In the case of shear-wave velocity 200 m/sec, seismic isolation might rather increases seismic responses. The frequency component of the incident bedrock wave corresponding to the natural frequency of the soil is amplified while the wave propagates through the soil. In the case that the shear-wave velocity of the soil is 200 m/sec, the natural frequency of soil, 0.5 Hz, coincides with that of the seismic isolation system so that the responses of seismically isolated structure are amplified. Similar observation can be found in the Mexico earthquake where the soil amplification gave large damages to structures with long period (Chopra, 2012).

Comparing the relative displacement histories of non-isolated structures on the rigid soil to that on the non-rigid soils with four different shear-wave velocities as shown in Fig. 4, we can see that soil-structure interactions significantly increased the relative displacement of non-isolated structures. In comparing the cases of isolated structures, however, the amplification due to the soil-structure interaction is not so severe as non-isolated structures. This means that soil-structure interaction in a seismically isolated system may not need to be considered in the case that the shear-wave velocity of soil is larger than the certain value which is significantly less than 2,440 m/sec.

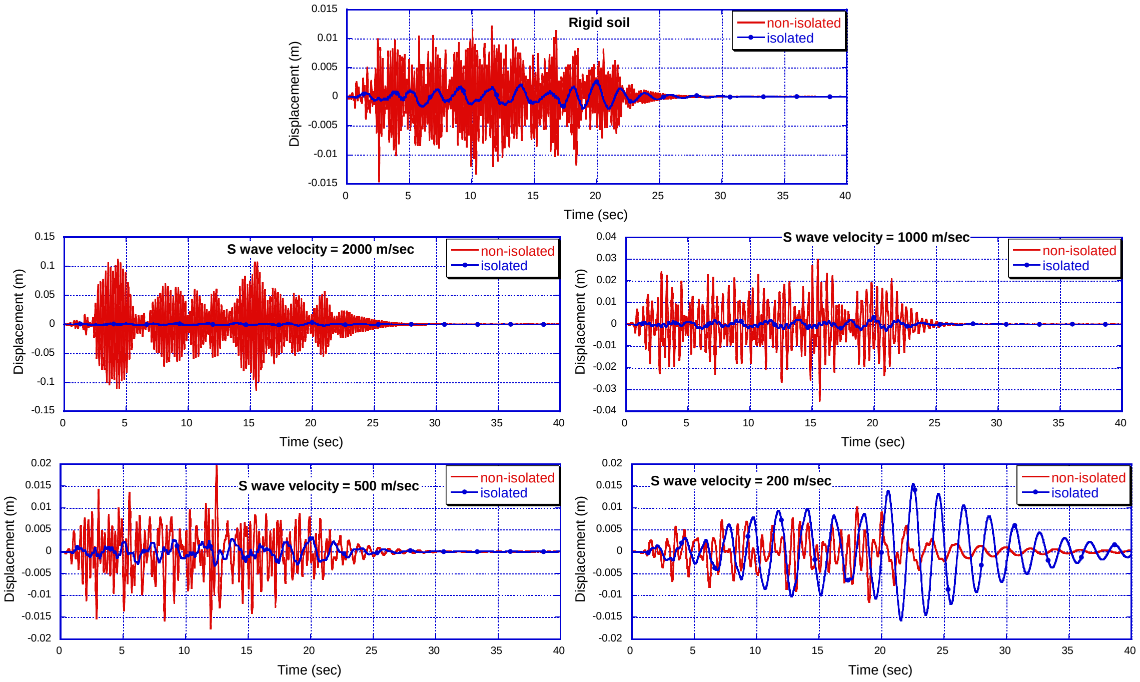


Figure 4. History of relative displacements at top of the containment building on different soil conditions under an earthquake of 7.0~7.5 magnitude

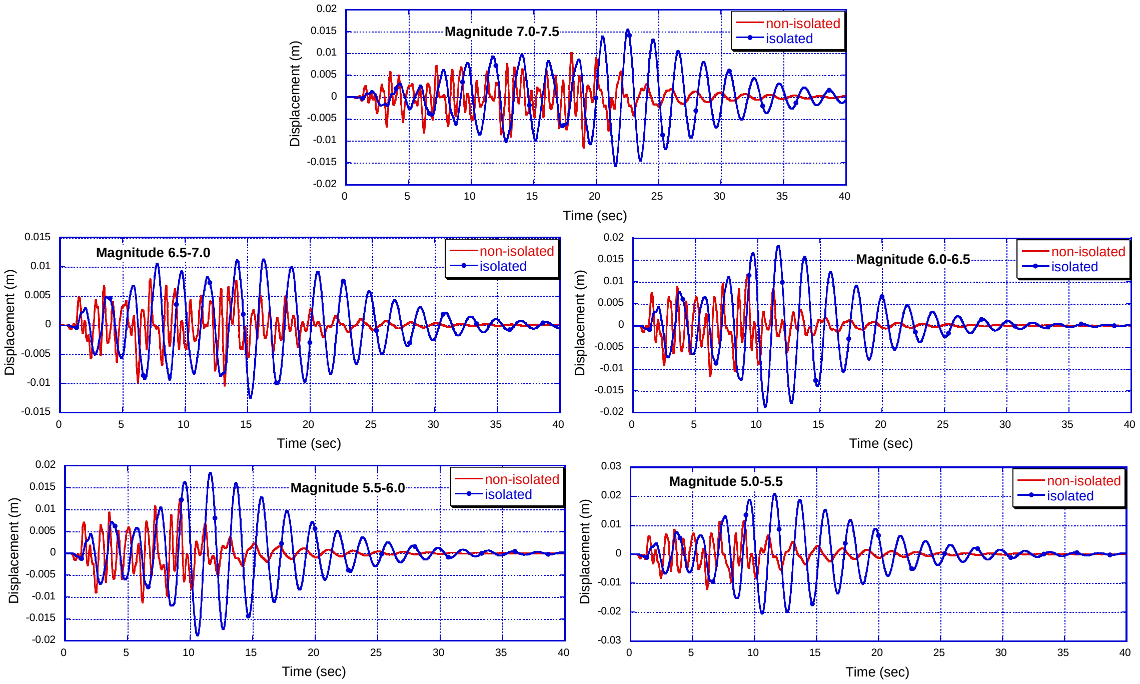


Figure 5. History of relative displacements at top of the containment building on the soil with 200m/s shear-wave velocity under earthquakes of different durations per magnitudes

Secondly, when the shear-wave velocity of the soil is 200 m/sec, the changes of seismic responses of structures are investigated by varying the duration of earthquake corresponding to the magnitude of bedrock control motion. The higher the magnitude of the bedrock motion, the longer is the duration of bedrock motion according to ASCE 4-98. An example of relative displacement histories of the top part with respect to the base plate of the containment building is plotted as shown in Fig. 5. The response of the isolated system under the rather short duration still can adversely amplify the responses of structures due to resonance effects.

CONCLUSION

We carried out analysis of seismic responses of seismically isolated containment buildings in consideration of soil-structure interactions and then investigated the effects of seismic isolation. Constructing numerical models for structures and their near-field by the finite elements while far-field from structures by consistent transmitting boundary, equations of motion of a soil-structure system for incident seismic wave were described. The described equations of motion were solved to carry out the seismic analysis of a seismically isolated soil-structure system. Generally, the results of this analysis show that seismic isolation significantly reduces the relative responses of the structure in the soil-structure system compared to the corresponding non-isolated structure. If the natural frequency of the soil is similar to that of the isolated soil-structure system, however, the relative responses of the structure are amplified due to the interaction of the system. On the non-rigid soil, the frequency component of bedrock motion corresponding to the natural frequency of the soil is amplified so that the same frequency component of input motion of the foundation is amplified. If the natural frequency of the seismic isolation system whose super-structure is assumed to be rigid is similar to that of the soil, the amplified input motion of foundation might increase the responses of seismically isolated structures. Therefore, the application of seismic isolation devices to structures on a flexible soil must be done after its safety is verified via precise analysis of the soil-structure interaction system. Furthermore, criteria that restrains application of seismic isolation devices should be prepared if necessary.

In an example of analysis, soil-structure interactions could be neglected on the soil whose shear-wave velocity is more than the certain value for isolated structures. If criteria or guidelines for this case are provided, more efficient seismic analysis would be possible.

If an earthquake with relatively low magnitude has significant amount of low-frequency components, the responses of seismically isolated structures can be significantly amplified. When containment buildings are constructed on the flexible soil where earthquakes with considerable amount of low-frequency components might occur, it is necessary to restrain application of seismic isolation devices.

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