SELECTION OF BOTTOM BOUNDARY ON SEISMIC RESPONSE OF MULTI-STORY UNDERGROUND COMPLEXES IN SOFT SITES

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Abstract

For obvious reasons, the buildings extend downwards into the earth. The large, deep, multi-story underground complexes offer the main solution to a lack of space in megacities, which extend even more than 30 meters deep beneath the ground. The selection of appropriate bottom boundary to input seismic waves is vital for the accurate simulation of the soil - underground structure interaction (SUSI) seismic behavior, especially in soft soil site. In this paper, to find the optimal solution of the inputting interfaces of earthquake waves, three multi-story underground complexes with different depths (*d*) which have three, four and five stories respectively in typical deep soft soil sites of Shanghai were studied. The distance from the soil bottom boundary to the bottom of the underground complex structure was marked as *D*. The ratio of *D/d* was set to 1.5, 2.5, 3, 4, 5, 6, respectively. Two-dimensional finite element models of the SUSI system of different *D/d* ratios were created and analyzed based on FEM software ABAQUS. The Davidenkov constitutive model was developed and implemented for soil nonlinearity. Four seismic waves records were chosen for the seismic analysis, including the 1989 Loma Prieta earthquake (GILROY), the 1999 Chi-Chi earthquake (HWA056), the 1985 Mexico City earthquake (TLHD), the 2011 Tohoku earthquake (NGNH32), and the last two were considered to be long-period seismic waves. The peak acceleration values of four waves were scaled to 0.035g, 0.07g, 0.1g, 0.2g, 0.3g, respectively. The PGA and response spectra of the ground surface and each story of the models above were observed. Differences in seismic response subjected to different seismic waves were compared and the effects of the *D/d* ratio on the seismic behavior of the SUSI system were discussed. Based on cases in this research, the results indicated that when the *D/d* ratio reaches above 4, the influence of the reflected wave at the bottom boundary has gradually weakened. It also concluded that long-period seismic waves may have a significant effect on the seismic response of the underground complex and the surrounding soil. In addition, the responses of the underground complex induced by different earthquakes are consistent with the characteristic seismic responses observed in soft soil sites.

Keywords: underground complex structures, bottom boundary, soft soil sites, soil - underground structure interaction (SUSI), seismic response

1. Introduction

With the continuous development and utilization of urban underground space, the underground structure has a trend of being larger and deeper, and the underground complex has emerged. As the key lifeline of various urban functions, the seismic performance of the underground complex structure is particularly important. Establishing a reasonable numerical model that can reflect the soil - underground structure interaction and then conducting dynamic analysis is an effective way to study and evaluate the seismic performance of underground structures.

Considering that in the actual issue of soil-structure interaction, the foundation soil is a semi-infinite body, and in the finite element simulation, it is often necessary to determine the calculation range of the soil. The wave reflection on the boundary of the soil and the difference in the vibrational morphology of the soil-structure interaction system will bring some deviations or errors to the results of numerical simulation. Therefore, determining a rational soil boundary and reducing the boundary effect is an important part of the finite element analysis of soil-structure interaction. The soil boundary includes a vertical lateral boundary and a horizontal bottom boundary. At present, the study of soil boundaries mainly focuses on the study of lateral artificial boundaries [1-4], and there are few studies on the bottom boundary. The bottom boundary is generally taken to the bedrock or the imaginary bedrock surface, on which the seismic waves are input.

In areas such as Shanghai, the actual construction site is often covered with deep soft soil layers. The bedrock is deeply buried. It will take a lot of time and money to obtain full soil profile data. The amount of computation will increase significantly as the deeper the bottom boundary set. The Code for Seismic Design of Underground Railway Buildings (DG/TJ08-2064-2009) [5] stipulates that the calculation depth of soil may be 70 m when time-history seismic analysis of structures in Shanghai soft soil site is carried out. However, the height of the underground complex structure that has been built or planned to be built is often higher than that of the general underground structure, and the depth of the bottom of the underground complex structure may exceed 30 m. 70 m, the calculated depth of soil layers is obviously not reasonable.

As mentioned above, in order to select the reasonable bottom boundary in the numerical simulation of the soil - underground structure interaction (SUSI) under earthquake excitations, a two-dimensional finite element method was used. Through numerical analysis and comparison, the influence of different positions of artificial bottom boundary on the seismic response of underground complex structure was discussed. The finite element models of three multi-story underground complex structures with different heights on the typical soft soil site in Shanghai were established in FEM software ABAQUS. Two ordinary seismic waves GILROY and HWA056 and two long-period seismic waves TLHD and NGNH32 were used as the input motion to investigate the reasonable bottom boundary.

2. Methodology

For the dynamic soil – underground structure interaction problem in semi-infinite space, selection of boundaries for simulation analysis is especially important. In addition, to reduce the influence of the lateral boundary, the depth of the bottom boundary must be considered well. In this paper, the finite element numerical simulation method considering soil-structure interaction is adopted. The schematic of the SUSI system with the selected bottom boundary was shown in Fig.1. The width and height of the underground complex structure were denoted as b and d, respectively. The distance from the bottom boundary of the soil layers to the bottom of the underground complex structure was marked as D.

As the inputting interface of earthquake waves, any waves reflected at the bottom boundary of the SUSI model cannot propagate back into the domain of interest, i.e. the underground complex, within full-time history analysis. This situation is considered to be the optimal solution for the bottom boundary selection. Reasonable bottom boundary selection can effectively save complicated computed time and improve calculation efficiency.

To obtain the optimal solution of the inputting interfaces of earthquake waves, different multi-story underground complexes in a typical deep soft soil site were studied. The ratio of D/d was set to 1.5, 2.5, 3, 4, 5, 6, respectively. As the ratio increased, that is, the position of bottom boundary continued to deepen, different finite element models were established. When the relative error of the seismic response of the underground complex structure did not change, the influence of the reflected wave on the seismic response of the underground complex structure was considered negligible. The reasonable bottom boundary was then obtained.

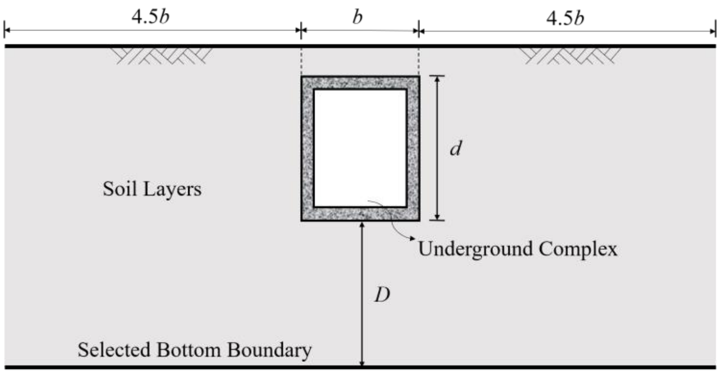


Fig. 1 – Schematic of the soil - underground structure interaction (SUSI) system with the selected bottom boundary

2.1 Physical Model of underground complexes

Three typical cases of underground complexes were investigated in this paper as illustrated in Fig.2: Case 1 is a three-story underground complex structure integrating the function of underground commercial street, underground pipe gallery and subway station. Case 2 is a four-story multifunctional underground complex structure, with urban transport links and transfer service as its leading functions. The basement level is for commercial development, and the other three floors are equipment platforms and subway stations. Case 3 a five-story underground complex structure that has underground garages on the top two stories and subway stations on the three stories below. To avoid the influence of other factors, the burial depth of all three cases is 3 m. The heights of these three underground complexes are 20.10 m, 23.56 m, 30.18 m, respectively. We set different depths (i.e., the heights of structures) d = 20.10 m, 23.56 m, 30.18 m, respectively.

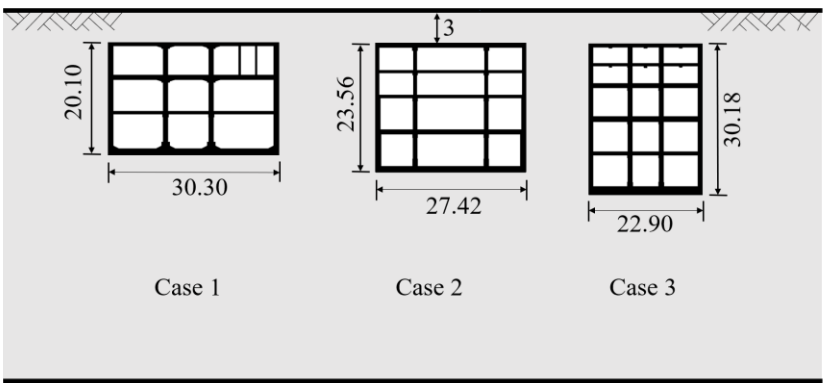


Fig. 2 – Typical cases considered in the selection of bottom boundary (unit: m)

2.2 Constitutive Model and Material Parameters

Based on previous dynamic experimental and numerical studies [6-7], it is assumed that Davidenkov constitutive model can simulate the nonlinearity of soft soils in Shanghai well. In the previous research [8], the authors developed Davidenkov constitute model and implement it here for soil nonlinearity.

The Davidenkov model is a three-parameter fitting model proposed by Martin et al. [9] and can be described as follows:

$$G/G_{\max} = 1 - H(\gamma) \tag{1}$$

$$H(\gamma) = \left[\frac{(\gamma/\gamma_0)^{2B}}{1 + (\gamma/\gamma_0)^{2B}} \right]^A \tag{2}$$

The typical soil parameter profile [7] with a depth of 280 m is used in this study. The soil layers are described in Table 1.

Table 1 – Parameters of deep soil deposits in Shanghai

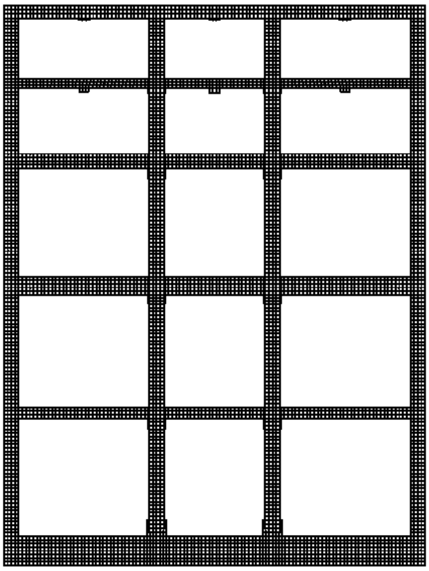
Layer	Depth (m)	Soil property	Bulk density (kg/m3)	Shear wave velocity (m/s)
S1	3	Clay	1900	100
S2	10	Mucky silty clay	1750	130
S3	20	Mucky clay	1750	160
S4	25	Clay	1820	190
S5	30	Clay	2000	260
S6	45	Sand	1920	290
S7	75	Silty clay	1900	320
S8	95	Sand	1950	340
S9	110	Clay	2000	400
S10	140	Sand	2020	420
S11	170	Clay	2040	440
S12	230	Sand	2060	500
S13	260	Clay	2080	510
S14	280	Sand	2100	580

2.3 Finite Element Model

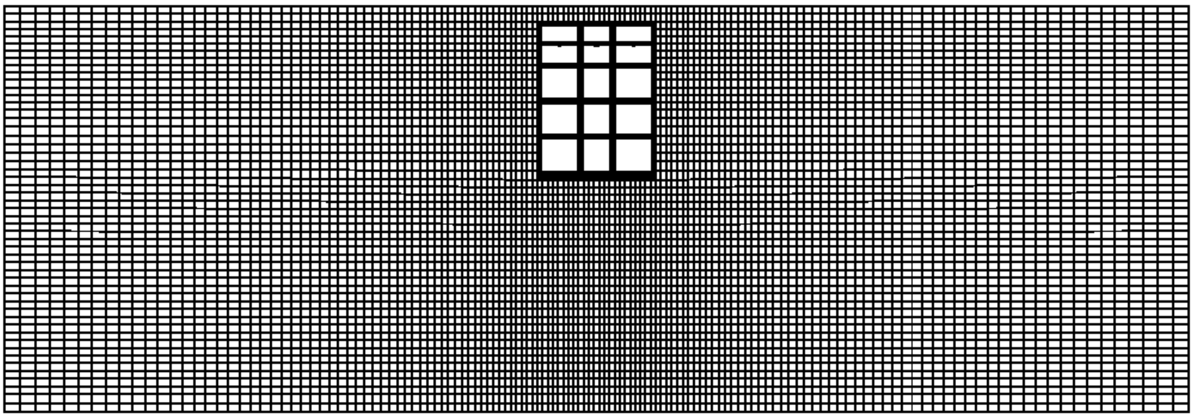
The finite element model of the soil - underground structure interaction (SUSI) system was established using the finite element software ABAQUS. One type of available element in ABAQUS was used: CPE4R (the Four-node plane strain element) for the model of both the soil and the underground complex. Furthermore, the SUSI was accounted for by setting the surface-to-surface contact between the soils and the underground complex. To simulate the soil-structure interface mechanism, a finite-sliding hard contact algorithm was employed, while the tangential behavior was modeled using the penalty friction formulation, setting the coefficient of Coulomb friction equal to 0.4 [10].

Follow the principle of a single variable, in this paper, the effects of retaining walls were not considered. For the lateral boundary, 4.5 times the width (b) of the underground structure along each side, shown in Fig.1, that is, 10b total length was long enough to use free lateral boundaries, which was enough to dissipate the transmitted energy and recover the free field soil conditions between the lateral boundaries and the structure [11].

For three cases shown in Fig.2, each six finite element models were established (D/d = 1.5, 2.5, 3, 4, 5, 6), respectively, among which the 2D finite element model of the soil - underground structure interaction (SUSI) systems of Case 3 when D/d = 1.5 was shown in Fig.3.



(a) 2D finite element model of the underground complex (Case 3)



(b) 2D finite element model of the SUSI system (Case 3, D/d = 1.5)

Fig. 3 – 2D finite element model

2.4 Input Motion

In order to figure out the optimal bottom boundary as the inputting interfaces, four seismic waves were chosen for the seismic analysis. Two ordinary seismic waves, GILROY and HWA056, were recorded in the 1989 Loma Prieta earthquake and in the 1999 Chi-Chi earthquake, respectively. Two typical long-period seismic waves, TLHD and NGNH32, were recorded in the 1985 Mexico City earthquake and in the 2011 Tohoku earthquake, respectively.

The acceleration time histories and acceleration response spectra of the input motions are shown in Fig.4 and Fig.5. The peak acceleration values of four waves were scaled to 0.035g, 0.07g, 0.1g, 0.2g, 0.3g, respectively.

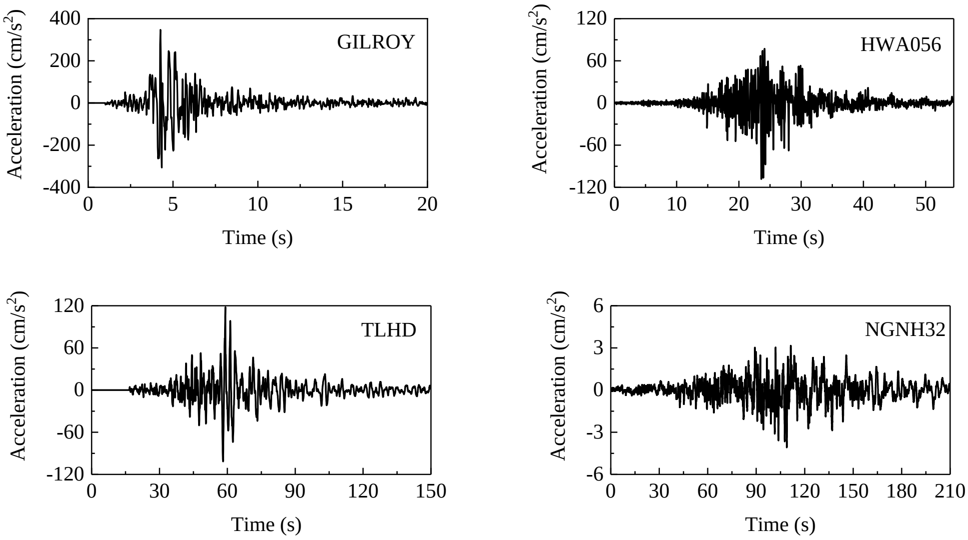


Fig. 4 – Acceleration time histories

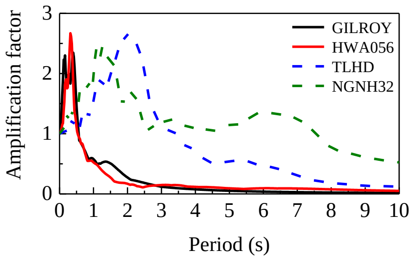


Fig. 5 – Normalized acceleration response spectra

3. Numerical examples and seismic analysis results

Using the finite element models above, considering each ratio of D/d which was set to 1.5, 2.5, 3, 4, 5, 6, respectively, the seismic response analysis of the SUSI system under each simulated condition was conducted. For Case 1, six bottom boundaries ranging from 53.25 m to 143.7 m were selected, and the corresponding shear wave velocity was from 320 m/s to 440 m/s; for Case 2, six bottom boundaries ranging from 61.9 m to 167.92 m were selected, and the corresponding shear wave velocities were from 320 m/s to 440 m/s; for Case 3, six bottom boundaries ranging from 78.45 m to 214.26 m were selected, and the corresponding shear wave velocities were also from 340 m/s to 500 m/s; for Case 3, six bottom boundaries ranging from 78.45 m to 214.26 m were selected, and the corresponding shear wave velocity was from 340 m/s to 500 m/s. The detailed depth of bottom boundaries and corresponding shear wave velocities were listed in Table 2.

Table 2 – Depth and shear wave velocity of the input location

(Bb: Bottom boundary; Swv: Shear wave velocity)

D/d	**Case 1**		**Case 2**		**Case 3**	
	Bb (m)	**Swv(m/s)**	**Bb (m)**	**Swv(m/s)**	**Bb (m)**	**Swv(m/s)**
1.5	53.25	320	61.9	320	78.45	340
2.5	73.35	320	85.46	340	108.63	400
3	83.4	340	97.24	400	123.72	420
4	103.5	400	120.8	420	153.9	440
5	123.6	420	144.36	440	184.08	500
6	143.7	440	167.92	440	214.26	500

3.1 Peak accelerations

Acceleration responses of ground surface and each story of three cases under different earthquake excitations from different depths of bottom boundaries were analyzed. The midpoint of the ground and the midpoint of each slab were served as the monitoring points. Peak acceleration values of the midpoints of the top roof slabs for inputting Loma Prieta GILROY wave and inputting Mexico City TLHD wave under different *D*/*d* ratios were presented in Fig.6 and Fig.7, respectively.

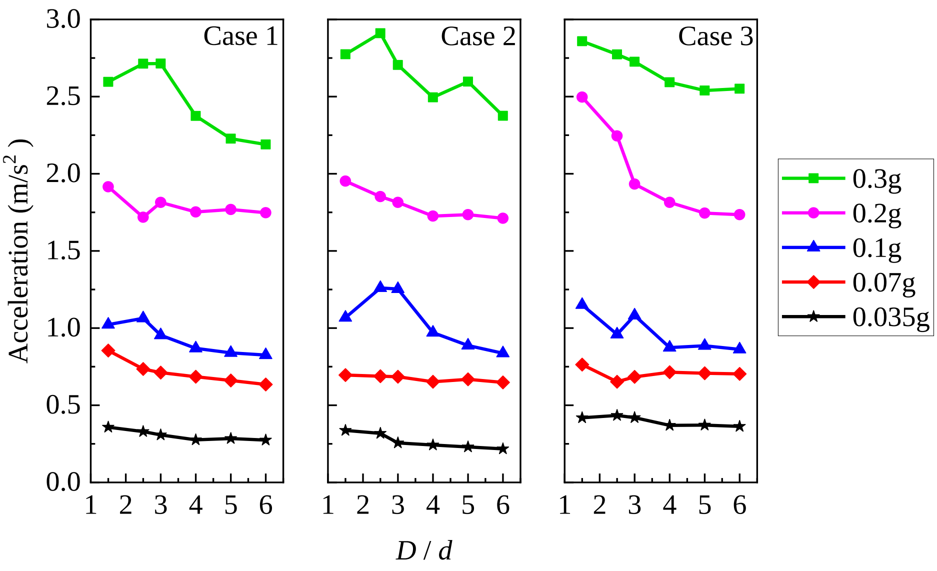


Fig. 6 – Peak accelerations for inputting Loma Prieta GILROY wave

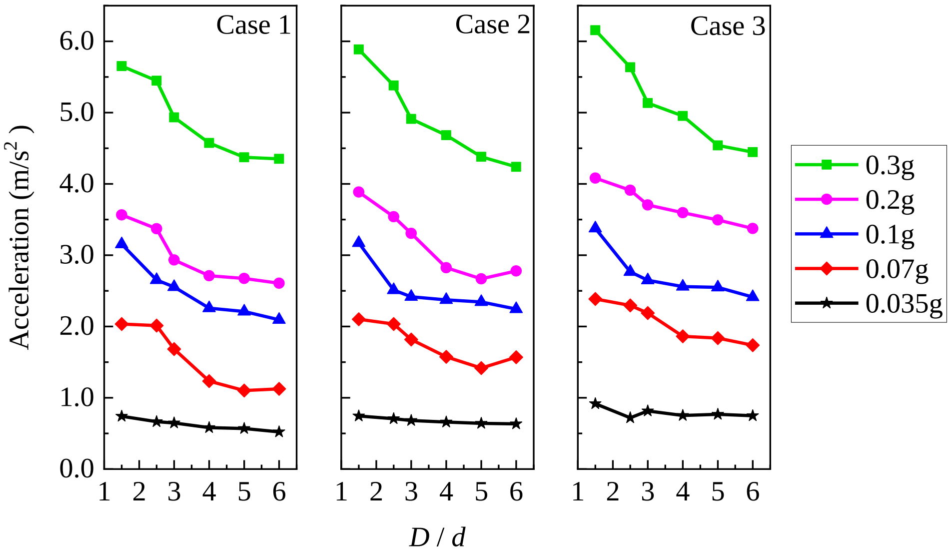
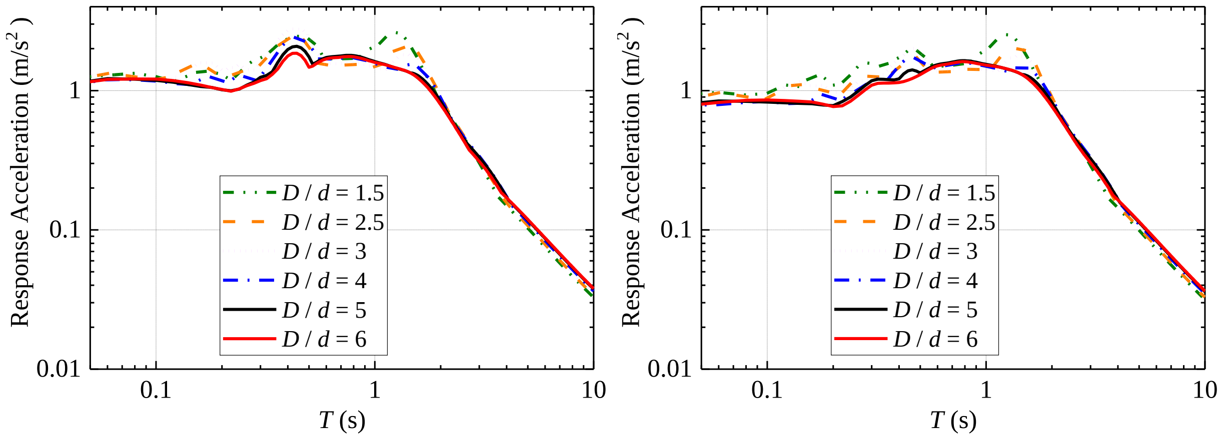


Fig. 7 – Peak accelerations for inputting Mexico City TLHD wave

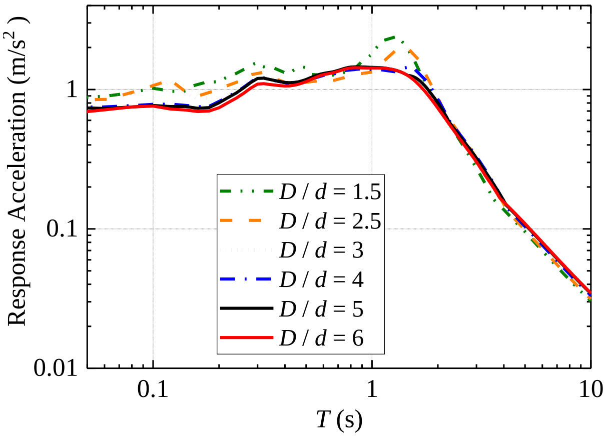
The results showed that for all three cases, under different peak ground motion excitations, the curves fluctuated wildly when the *D*/*d* ratios were small. The curves became gentle when the *D*/*d* ratios reached 4 or more. As the ratio increased, the average change in the maximum acceleration response gradually did not exceed 10%, and the corresponding shear wave velocities were 400 m/s, 420 m/s, 440 m/s, respectively, for each case.

3.2 Acceleration response spectra

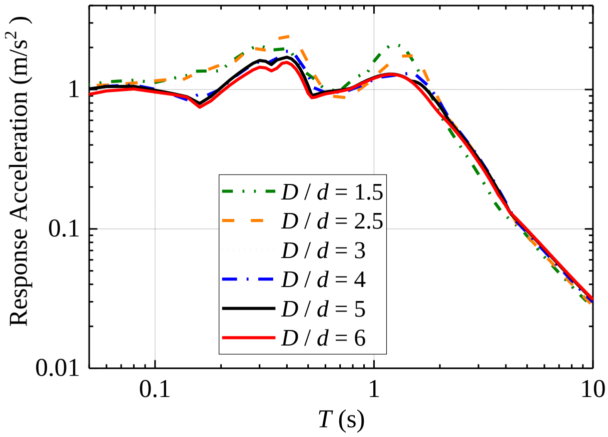
To evaluate the rational bottom boundary, the acceleration response spectra of the ground surface and each story of the models above were also observed. As an example, the acceleration spectra of Case 3 were presented in Fig.8 when the acceleration amplitude of Loma Prieta GILROY wave was scaled to 0.1g and inputted from different depth under corresponding *D*/*d* ratio.



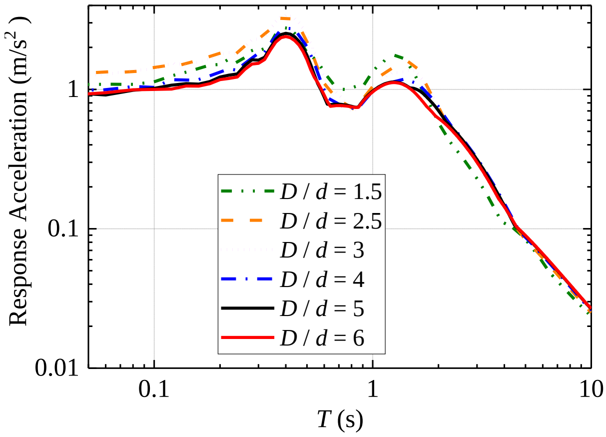
(a) Level -1 Roof slab (b) Level -2 Roof slab



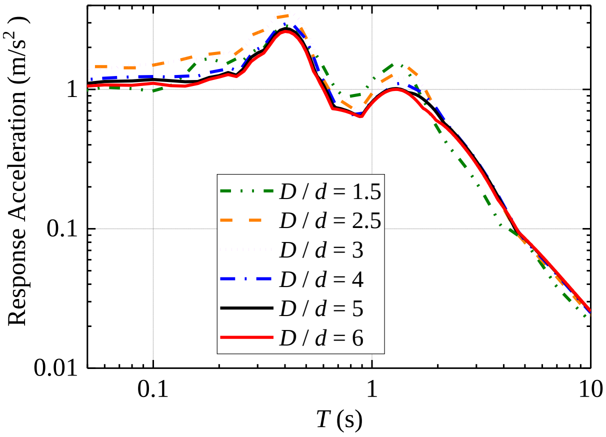
(c) Level -3 Roof slab



(d) Level -4 Roof slab



(e) Level -5 Roof slab



(f) Level -5 Bottom slab

Fig. 8 – Acceleration spectra for 0.1g inputting Loma Prieta GILROY wave

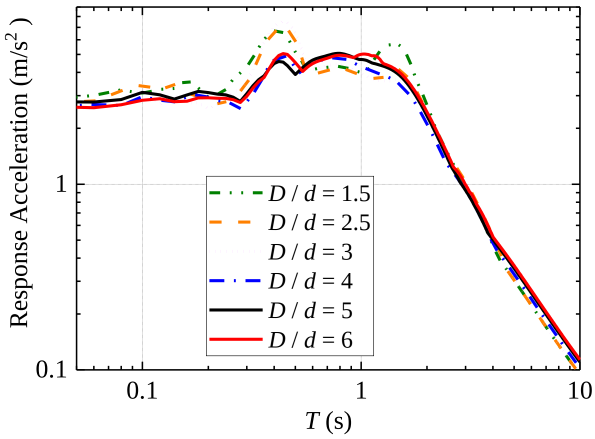


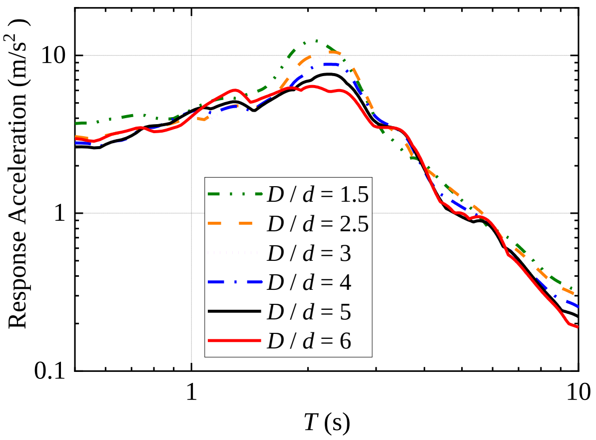
Fig. 9 – Acceleration spectra of Level -1 roof slab for 0.3g inputting Loma Prieta GILROY wave

As the *D*/*d* ratio increased, the peak value of the acceleration response spectrum was decreasing. When D/d increased to 4, the curve changed slowly. The solid black curve (*D*/*d* = 5) and the solid red curve (*D*/*d* = 6) almost overlapped each other. With the depth of the bottom boundary and shear wave velocity increasing, the value of the seismic response spectra gradually closed to the actual one.

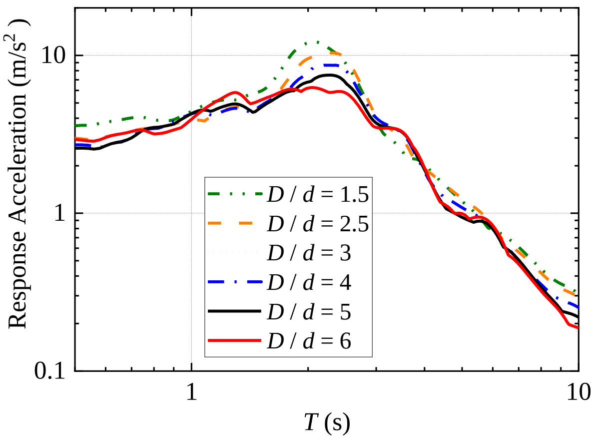
Fig.9 showed the acceleration spectra of the top roof slab in Case3 under 0.3g inputting Loma Prieta GILROY wave excitation. Compared with Fig.8 (a), it can be seen that as the peak accelerations of the input motion increased, the response spectra value became larger, but the trend with the increasing *D*/*d* ratios was almost the same. This means that the magnitude of the input motion has little effect on the selection of the bottom boundary.

3.3 The effect of long-period seismic waves

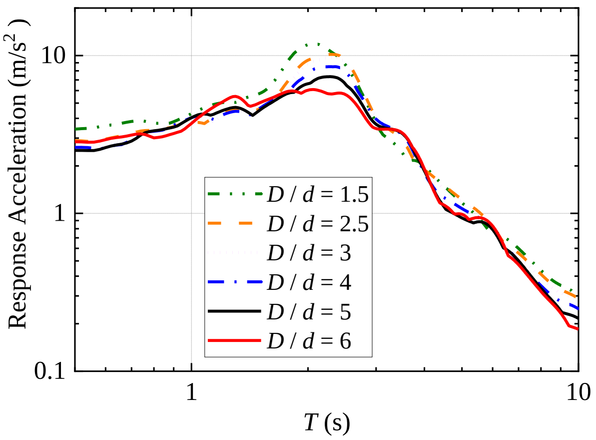
In soft soil sites, the impact of long-period ground motion on the structure cannot be ignored. As shown in Fig.10, acceleration spectra under 0.1g inputting Mexico City TLHD wave excitation had a significant difference to those under 0.1g inputting Loma Prieta GILROY wave excitation in Fig.8. The maximum values of response spectra were even larger than those with 0.3g input motions in Fig.9. Even when the *D*/*d* ratio reached 5 and 6, the curves did not have a tendency to coincide gradually in the period among 1.5 s to 2.5 s. However, when the period reached 3.0 s or more, and the *D*/*d* increased to 4, the effect of the deepening of bottom boundaries on the acceleration response spectra was drastically weakened.

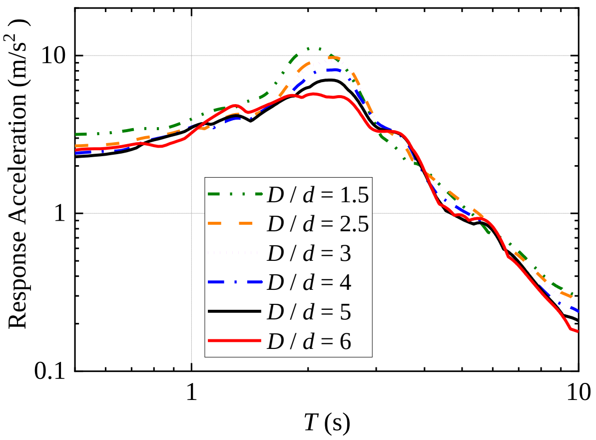


(g) Level -1 Roof slab



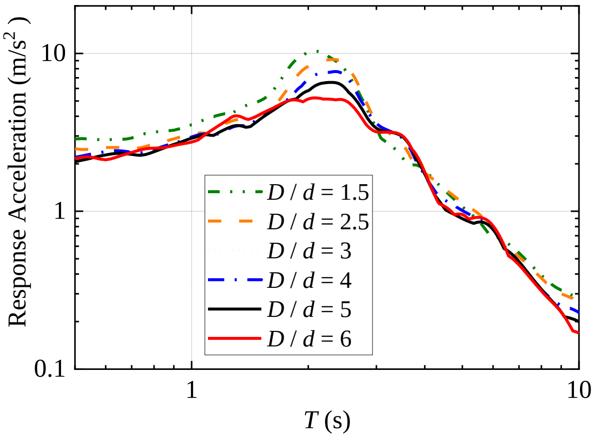
(h) Level -2 Roof slab

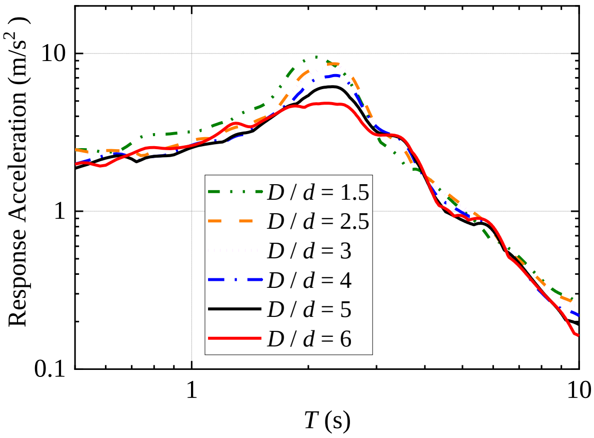




(i) Level -3 Roof slab

(j) Level -4 Roof slab





(k) Level -5 Roof slab

(l) Level -5 Bottom slab

Fig. 10 – Acceleration spectra for 0.1g inputting Mexico City TLHD wave

4. Conclusions

In this study, seismic responses of three typical cases of underground complexes in Shanghai soft soil site were investigated to figure out the optimal depth of bottom boundaries in the SUSI system for FEM analysis. Four seismic wave records were selected to conduct the seismic analysis, including two ordinary earthquake records - the 1989 Loma Prieta GILROY wave, the 1999 Chi-Chi HWA056 wave, and two long-period earthquake records - the 1985 Mexico City TLHD wave, the 2011 Tohoku NGNH32 wave. Six different *D*/*d* ratio values were taken into consideration: 1.5, 2.5, 3, 4, 5, 6, respectively. The peak accelerations, response spectra of three cases were analyzed and compared. The main conclusions can be drawn as follows.

For all three cases in deep soft sites, the effect of the bottom boundary as the input interface on seismic response are approximately similar. As the depth of the bottom boundaries and shear wave velocity increasing, the value of the peak accelerations approaches to a flat and the acceleration response spectra gradually close to the actual value. The peak acceleration of the input motion has little effect on the selection of the bottom boundary.

The long-period seismic waves may have a significant effect on the seismic response of the underground complex and the surrounding soil. For the general earthquake, the *D*/*d* ratio equals to at least 4 and the soil layer with shear wave velocity of 400 m/s or so where can be chosen as the bottom boundary. The SUSI system with a long natural vibration period should be treated seriously considering the long-period seismic waves. The *D*/*d* ratio goes to 6 with the soil layer with shear wave velocity of above 500m/s, which is suggested to reduce the influence of the reflected wave at the bottom boundary.

The reasonable position of the bottom boundary should also be related to the width of the underground structure (as *b* in Fig.1). Further research will be carried out. The conclusions are only based on the results of the cases in this paper.

5. Acknowledgements

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6. Copyrights

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