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Seismic response of SSSI system: surface structures and subway

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The seismic response of an underground structure is analysed in the time domain by considering the non-linearity of soil and the structure–soil–underground structure interaction. A three-dimensional model that comprises a subway station and adjacent surface frame structure with a pile foundation and soft clay is established. The modified Davidenkov model is used to simulate the non-linearity of soft clay, which is then further developed using the commercial software Abaqus. This study focuses on the influence of adjacent surface frame structures on the seismic response of a subway station in the time domain. The interstorey drift ratio of the subway station is selected to evaluate the correlation effect in this complicated system. The influence factors, including the horizontal distance between the frame structures and subway station, length of the pile foundation, orientation of the frame structure and burial depth of the subway station, are discussed in the paper. Numerical results indicate that horizontal distance and burial depth are two of the key factors that may evidently amplify or attenuate the seismic response of an underground structure.

Notation

d	horizontal distance between the frame structure and subway station: m
H	height of a storey: m
H_s	thickness of the soil
h	buried depth of the subway station: m
l	length of the pile foundation: m
ΔU	peak displacement difference at the side-plate of the subway station
Δu	maximum displacement difference between two adjacent floors across the floor plane: m
θ	interstorey drift ratio
ϕ	angle between the longitudinal axis of the frame structure and subway station: °

Introduction

Subway stations were once believed to be insusceptible to earthquakes. Nevertheless, due to several severe seismic events (e.g. the 1995 Kobe earthquake, the 1999 Kocaeli earthquake, the 1999 Chi-Chi earthquake and the 2008 Wenchuan earthquake), the necessity of a seismic design for subway stations has been recognised (Bobet *et al.*, 2008; Hashash *et al.*, 2001) in seismic areas. The seismic behaviour of subway stations has been analysed for a long time. A system with a single underground structure embedded into soil is the typical simplified model used by numerous researchers, including Chen *et al.* (2013, 2015), to represent the seismic problem of subway stations. However, this model considers only the correlation effect between the soil and the subway station. In such a coupled system, this effect is called soil–structure interaction (SSI). Many scholars have made remarkable contributions (Luco and Westmann, 1971, 1972; Reissner, 1936) to this issue, particularly to its inchoate development process. The practical application of various

methods, such as the finite-element method (FEM) and boundary-element method, and the rapid development of computer technology have accelerated the development of SSI analysis. Further studies on SSI (Azadi and Hosseini, 2010; Hatzigeorgiou and Beskos, 2010; Miao *et al.*, 2016; Romanel and Kundu, 1993) have been conducted in recent decades. The history and current status of SSI were elucidated by Kausel (2010).

Apart from soil, however, a subway station is dependent on other elements in its surroundings. Adjacent surface buildings and roads also impact on the seismic behaviour of a subway station. The impact on the elements of a multistructure system through soil is called structure–soil–structure interaction (SSSI). The analysis of the dynamic response of a subway station during an earthquake has become increasingly difficult due to the existence of adjacent surface structures.

Previous studies on SSSI (Aldaikh *et al.*, 2015, 2016; Behnamfar and Sugimura, 1999; Kobori and Kusakabe, 1978, 1980; Warburton *et al.*, 1971, 1972) have mostly focused on either superstructures or underground structures. Only a few studies have simultaneously considered underground and adjacent surface structures. Yang *et al.* (2007) conducted an analysis on the seismic response effect of a tunnel to nearby structures. Guo *et al.* (2013) investigated the interstorey drift ratio of adjacent surface structures by considering the existence of a subway station with a two-dimensional (2D) model. Recently, the correlation effect law between adjacent surface and underground structures was investigated in the frequency domain by Wang *et al.* (2013, 2017).

The seismic behaviour of a subway station can be seriously affected by soil properties. Most of the previous analyses on SSSI

are limited to frequency-domain analyses, which are less time consuming but can be conducted only under linear conditions. However, the non-linear behaviour and other properties of the soil cannot be disregarded on various occasions. Time-domain analysis, which can use time as a coordinate to express the relationship among parameters, can consider the non-linearity and other properties of soil. Time-domain analysis is an important supplement to frequency-domain analysis. Previous studies in the time domain, such as those of Hatzigeorgiou and Beskos (2010), Abate and Massimino (2017a, 2017b) and Abate *et al.* (2016), were nearly always conducted on a single structure or with a 2D model. Hence, an analysis of the seismic response of a subway station in the time domain that considers the non-linearity of soil and SSSI with a three-dimensional (3D) model is necessary.

The problem is stated and the basic parameters of the 3D numerical model of SSSI are described in the next section. Subsequently, the 3D model of a surface structure–soil–underground structure system that considers the non-linearity of soil is established by way of FEM. Ground motion is inputted to analyse the seismic response of a subway station. The influence of factors, including the horizontal distance between the frame structures and subway station, length of the pile foundation, orientation of the frame structure and burial depth of the subway station, on the interstorey drift ratio of a subway station is presented in the form of time-domain curves and formulas.

Problem definition

Here, the system under study comprises a subway station and an adjacent surface frame structure with a pile foundation and soft clay that exhibits a non-linear behaviour. This investigation is focused on the seismic response of the subway station under different arrangement and size parameters.

The parameters of each component of the surface frame structure are as follows: the number of storeys is ten; the height of each storey is 3.6 m; the cross-sections of the frame column and frame beam are 600 mm × 600 mm and 250 mm × 600 mm, respectively; the diameter of the pile is 600 mm; the length of the pile is 18 m; and the thickness values of the floor slab and base

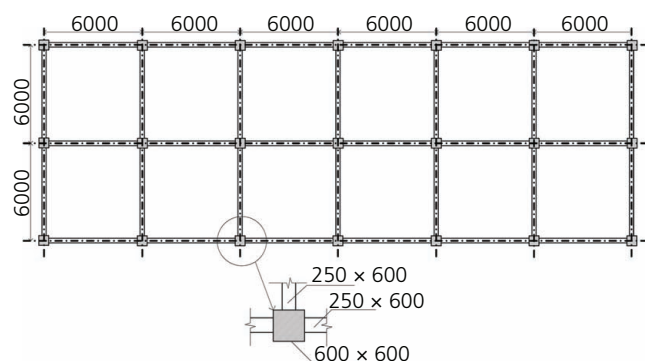


Figure 1. Typical cross-section of adjacent surface structure (dimensions: mm)

plate are 150 and 500 mm, respectively. A typical cross-section of the surface structure is shown in Figure 1. A subway station in Shanghai is selected to establish the subway station model. The length of the station is 72 m, and its cross-section and profile are shown in Figures 2 and 3, respectively. The Poisson's ratio of concrete is 0.2. Its modulus is 3.45×10^4 MPa, except for the pile

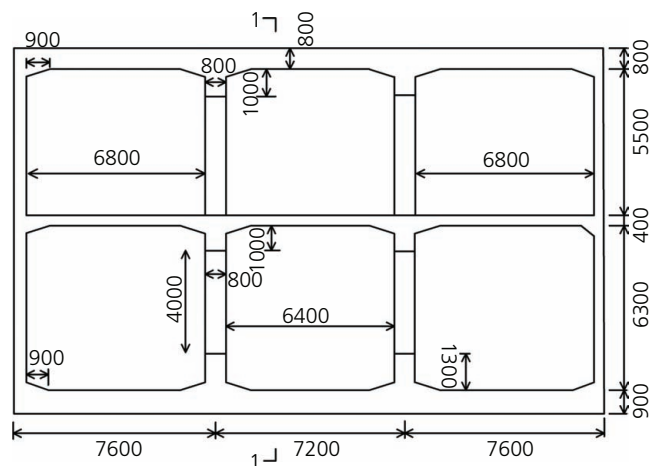


Figure 2. Cross-section of subway station (dimensions: mm)

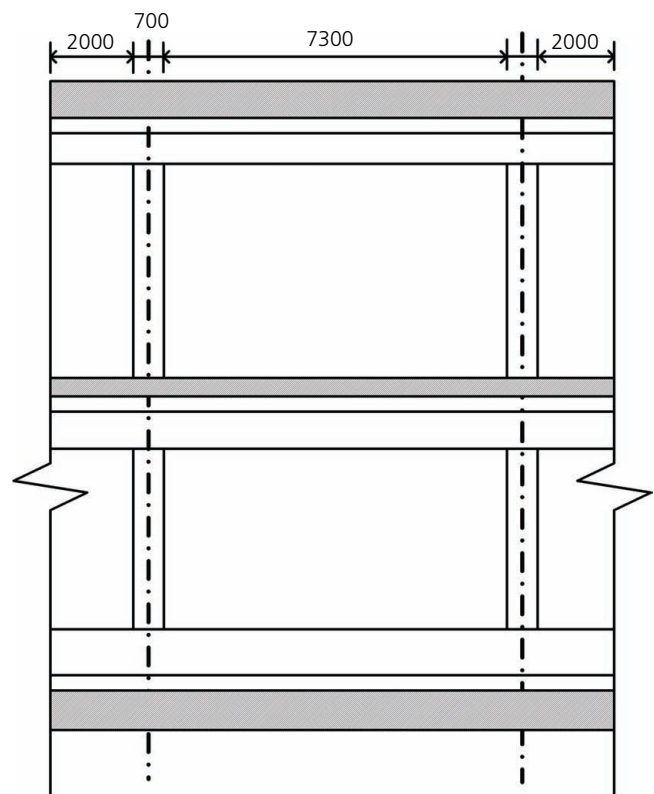


Figure 3. Profile of cross-section 1-1 of the subway station (dimensions: mm)

foundation, which has a modulus of 3.0×10^4 MPa. Moreover, the elastic parameters of soil are as follows: mass density is 1980 kg/m^3 and Poisson's ratio is 0.485.

The seismic behaviour of the subway station with different arrangement and size parameters is discussed in this section. A different arrangement is realised by changing the horizontal distance (d) between the frame structure and subway station, orientation of the frame structure (represented by the angle (ϕ) between the longitudinal axis of the frame structure and subway station) and buried depth (h) of the subway station. Meanwhile, a different size is obtained by changing the length (l) of the pile, as shown in Figure 4. To explore the extent of the impact of these factors on the seismic response of the subway station that considers SSSI, the seismic responses of the subway station are compared under different parameter conditions.

Finite-element model

The finite-element model of the surface structure–soil–underground structure system is established and analysed in the time domain using general finite-element software, namely, Abaqus, as shown in Figure 5.

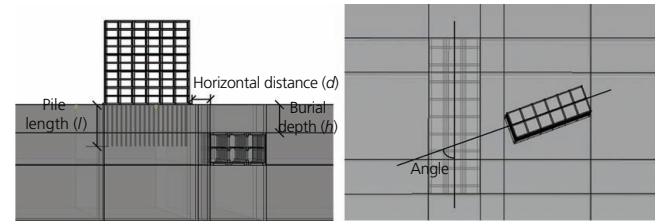


Figure 5. Influence factors in the finite-element model

The surface frame structure and subway station are modelled by solid elements, except for the pile foundation, which is modelled by beam elements. Several dynamic constitutive models of soil (Liu and Ling, 2008; Liu *et al.*, 2006, 2014; Macari *et al.*, 2003; Martin and Seed, 1982) have been proposed in the past decades. These models can simulate the dynamic behaviour of various types of soil. Here, the three-parameter modified Davidenkov model (Zhao *et al.*, 2017) is used as the constitutive model of soft clay. This modified model can efficiently describe the non-linear dynamic characteristics of all types of soil, and the accumulated test data are abundant. This model follows the rule of the ‘upper

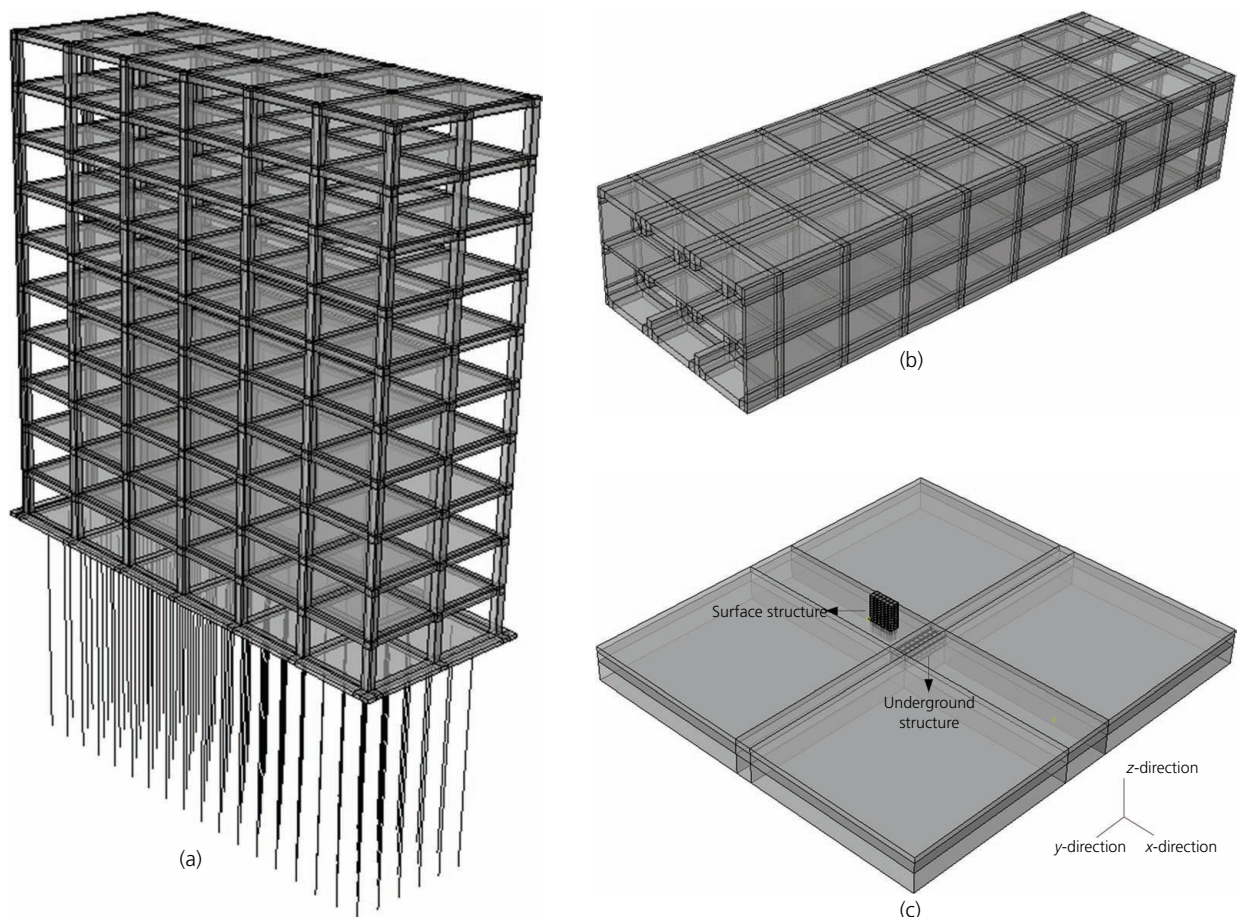


Figure 4. Finite-element model: (a) surface structure; (b) underground structure; (c) surface structure–soil–underground structure system

skeleton curve' in the 'extended Masing' rule and modifies the loading and unloading criteria of the hysteresis curve based on the ' n times method' proposed by Pyke *et al.* (1979), thereby solving the problem of the extended Masing rule requiring a large storage space. Furthermore, the modified model improves the equivalent strain algorithm, which enhances computational efficiency without losing computational accuracy. The stress–strain curve of the modified Davidenkov soil model is shown in Figure 6. Three parameters are required to define a kind of soil using this soil model: A , B and γ , whose meaning can be referred to in the paper by Zhao *et al.* (2017). Here, the values of those parameters are 1, 0.35 and 0.000 967 631, respectively. A tie contact condition, which is used to connect two faces so that the nodes of the slave face have the same physical quantity as those of the master face, is assumed between the subway station and the surrounding soil given that the subway station moves along with the soil around it under ground motion. The surface frame structure and pile foundation also exhibit the same phenomenon. The piles are embedded into the soil.

The scope of the soil is set to be sufficiently large to avoid using artificial boundaries, increase computational efficiency and meet the conditions of semi-infinite space (Wang *et al.*, 2017). The boundary of the surface frame structure and subway station is over $5H_s$ long of that of the soil, where H_s is the thickness of the soil, set at 50 m. An El Centro wave with an acceleration peak of $0.1g$ is selected as the seismic input, applied in the x -direction as shown in Figure 4(c), and its time history of acceleration is shown in Figure 7.

Numerical results

The 3D model of the surface structure–soil–underground structure system is described in the previous section. Subsequently, the influences of four parameters – namely, horizontal distance between the frame structures and subway station, length of the

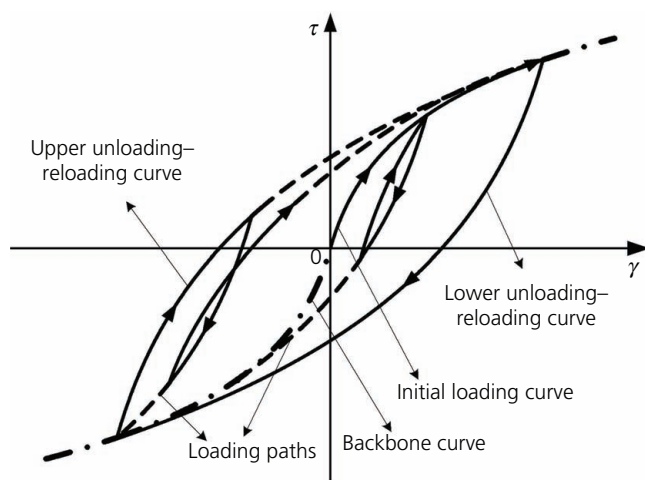


Figure 6. Stress–strain curve of the modified Davidenkov soil model (Zhao *et al.*, 2017)

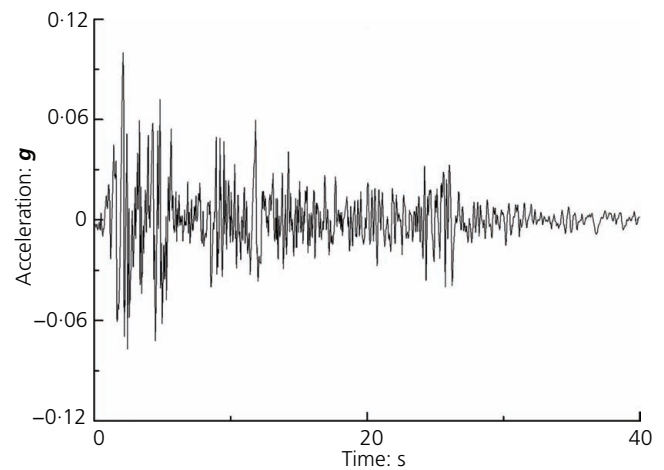


Figure 7. Acceleration time history of El Centro wave

pile foundation, orientation of the frame structure and burial depth of the subway station – on the response of the underground structure are discussed in this section. Here, the interstorey drift ratio θ is selected as the index to evaluate the correlation effect in such a complicated system, which is defined as $\Delta u/H$, where Δu is the maximum of the displacement difference between two adjacent floors across the floor plane and H is the height of a storey. To determine the law of the correlation effect, various seismic responses of the subway station are analysed and contrasted under different parameter conditions. The controlling variable method, in which only one of the factors is changed while the other variables are controlled to remain constant, is used in the next four sections to investigate the impact of the selected factors for multifactorial (multivariable) questions. Several figures are provided in the following sections to show the influences of the four parameters. The length of the pile foundation is 18 m, the frame structure is perpendicular to the subway station, the thickness of the soil coverage is 8 m and the horizontal distance is 12 m, when those parameters are controlled to remain constant.

Effect of horizontal distance

Here, the horizontal distance (d) between the adjacent frame structure and subway station is changed while the other three variables are controlled to remain constant. The horizontal distance varies from 5 to 40 m. The calculation results of the model are extracted to draw curves. The time history curves (Figures 8 and 9) show that the responses of the interstorey drift ratio at different horizontal distances are similar in shape. To reflect clearly the distinction of the interstorey drift ratio, the details of the interstorey drift ratio responses of the station are presented on an enlarged scale in Figures 10 and 11. These responses are selected during the pre- and post-peaking phases, thereby showing difference in amplitude. Peak points, including the positive maximum and negative maximum, are connected by lines in Figures 12 and 13 to investigate the impact of the interstorey drift ratio on the peak value. The interstorey drift ratio

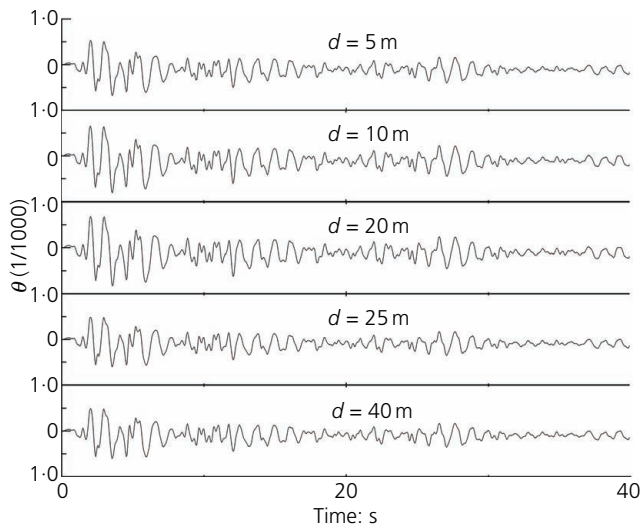


Figure 8. Interstorey drift ratio responses of the first floor of the station (horizontal distance changed)

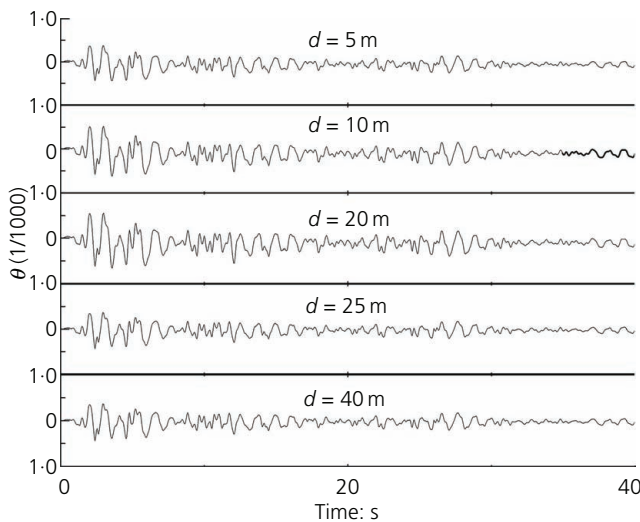


Figure 9. Interstorey drift ratio responses of the second floor of the station (horizontal distance changed)

response of the subway station is fluctuating, but not monotonous, under different conditions of horizontal distance between the two structures. In addition, when the distance is sufficiently far, the influence of adjacent surface structures on the response of the subway station is minimal and the maximum interstorey drift ratio is a constant.

Effect of pile length

The pile foundation is also likely to affect the seismic response of the subway station. The controlling variable method is used as described earlier to study the effect of pile length (l) on the seismic response of the subway station. Here, the length of the

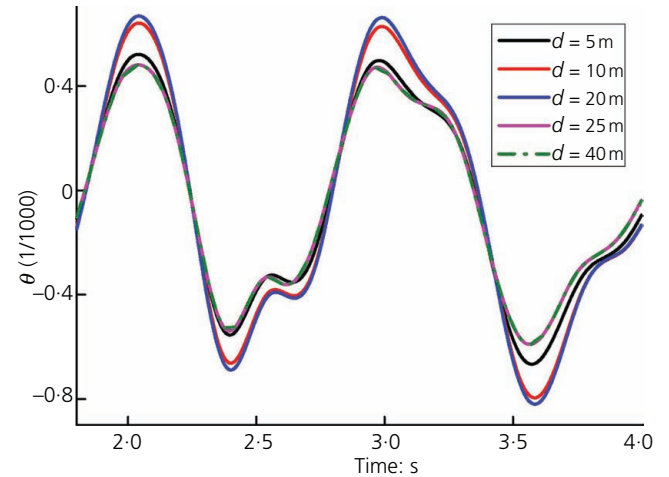


Figure 10. Detail with an enlarged scale of the peak interstorey drift ratio response of the first floor of the station (horizontal distance changed, 1.8–4 s)

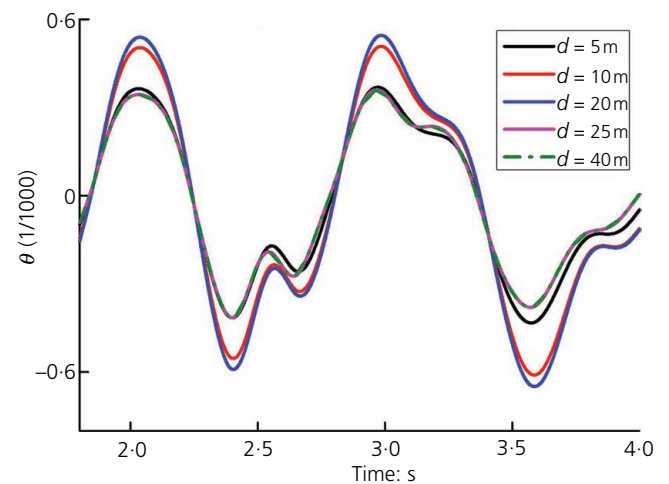


Figure 11. Detail with an enlarged scale of the peak interstorey drift ratio response of the second floor of the station (horizontal distance changed, 1.8–4 s)

pile foundation is changed from 0 to 24 m by 6 m intervals. The time history curves of the interstorey drift ratio nearly overlap although the length of the pile changes, which differs only slightly when the length of the pile is 24 m. The line of the maximum interstorey drift ratio of the first floor rises slightly at the end, as shown in Figure 14, and the line that connects the maximum interstorey drift ratio of the second floor is nearly horizontal, as shown in Figure 15. When the time history curves are the same in terms of shape and amplitude, the influence of pile length on the interstorey drift ratio of the station can be disregarded. The comparison of the results presented in Figure 8 and those of Wang *et al.* (2017) shows that the influence of pile length on the seismic response of underground structures in the

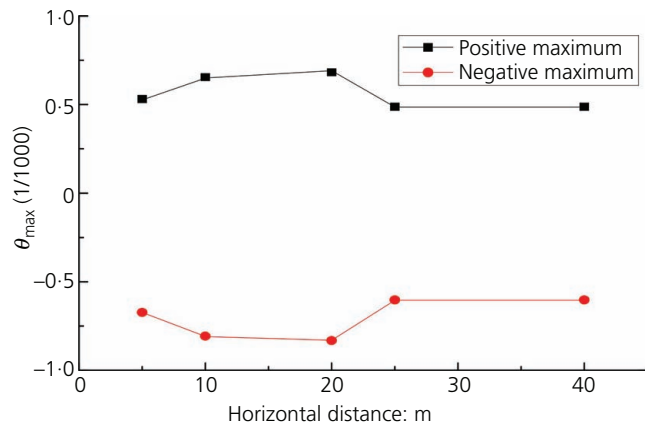


Figure 12. Variation in the maximum interstorey drift ratio of the first floor of the station with horizontal distance to the structure

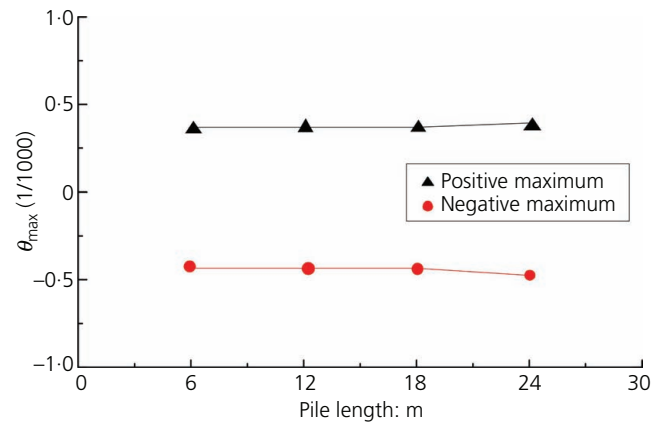


Figure 15. Variation in the maximum interstorey drift ratio of the second floor of the station with the pile length of the structure

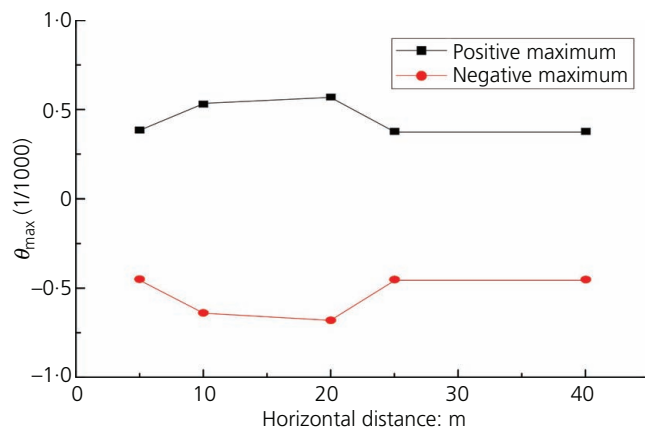


Figure 13. Variation in the maximum interstorey drift ratio of the second floor of the station with horizontal distance to the structure

frequency and time domains is relatively limited and nearly negligible.

Effect of orientation

Another important parameter that may have an impact on seismic response is the orientation of the frame structure, which is represented by the angle (ϕ) between the longitudinal axis of the subway station and frame structure. Here, ϕ is changed for modelling and calculation, whereas the other three factors remain unchanged. The responses of the interstorey drift ratio at different orientations of the frame structure in the time domain show a similarity in shape and a difference in amplitude. In Figures 16 and 17, the curve of the interstorey drift ratio is nearly coincident when the angle is 0–60°, whereas the value of the interstorey drift ratio decreases when the angle increases to 70 and 80°. The response rises and reaches the maximum value when the frame structure is perpendicular to the subway station ($\phi = 90^\circ$). That is, the response remains constant in the beginning, then decreases and finally increases to the maximum value with an increasing

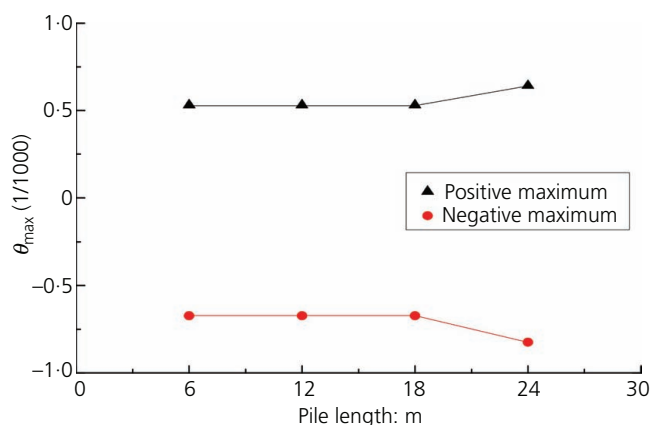


Figure 14. Variation in the maximum interstorey drift ratio of the first floor of the station with the pile length of the structure

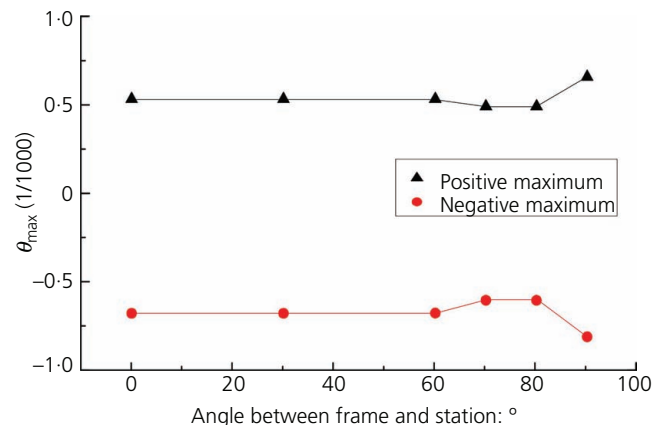


Figure 16. Variation in the maximum interstorey drift ratio of the first floor of the station with orientation to the structure

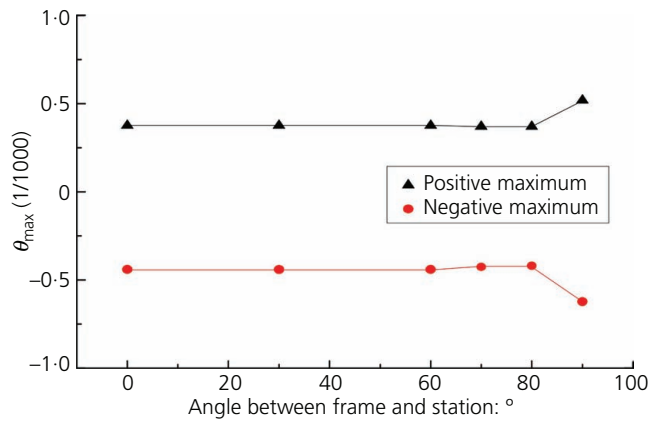


Figure 17. Variation in the maximum interstorey drift ratio of the second floor of the station with orientation to the structure

angle. Moreover, the minimum value appears between 70 and 80°, which is consistent with the case in which the diagonal of the frame horizontal plane is perpendicular to the longitudinal axis of the subway station – that is, approximately 72°. The reason for the appearance of a minimum may be that in this case, the stiffness of the surface structure in the x -direction is the greatest and the strengthening effect of the pile on the soil is the most significant, which limits the movement of the underground structure in the x -direction.

Effect of burial depth

Subway stations may be constructed at different depths to meet requirements in topography, transportation and urban spatial arrangement, among others. The seismic responses of the subway station may also vary under different depth conditions. In this section, the subway station's burial depth (h) ranges from 4 to 25 m, while the other parameters remain constant. Three seismic waves with different peak accelerations, 0.1g, 0.2g and 0.3g, are chosen as the input earthquake motions, to simulate earthquakes with different intensities. To investigate the relationship between the seismic response of the subway station and the burial depth, the displacement difference at the side-plate was chosen as the indicator, which represents a meaning similar to the interstorey drift ratio. The responses in either the time history curve or the partial enlargement differ considerably from each other in terms of amplitude, thereby indicating that this parameter has a major impact on the seismic response of the subway station. The peak displacement differences at the side-plate of the subway station, defined as ΔU , with different burial depths are shown in Figures 18 and 19. Obviously, the relationship between the peak displacement difference of the station and burial depth can be described effectively by linear equations when the acceleration peak is 0.1g. While when the peak acceleration is 0.2g or 0.3g, the peak displacement difference increases with the increase in burial depth overall and declines when the burial depth is 12 m. There are two factors affecting the displacement response of the subway station: one is the constraint of the surrounding soil and

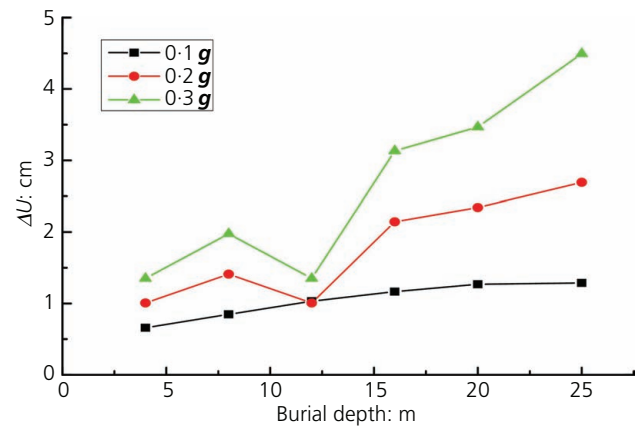


Figure 18. Variation in positive peak displacement difference at the side-plate of the subway station with burial depth

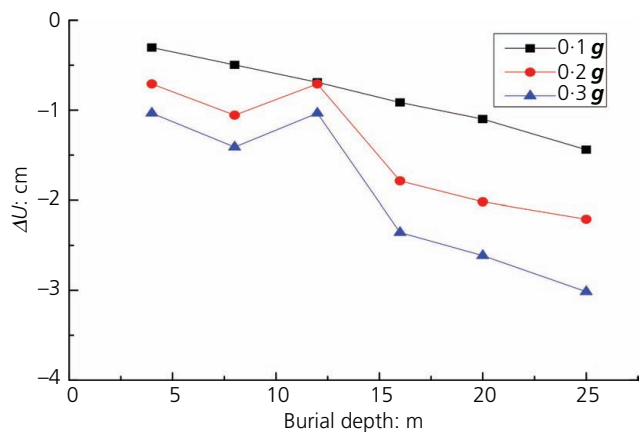


Figure 19. Variation in negative peak displacement difference at the side-plate of the subway station with burial depth

the other is the distance between the underground structure and the base rock where the wave comes. The effects of these two factors on the response of subway station are opposite to each other. The deeper the buried depth is, the stronger the constraint of the surrounding soil and the less the displacement difference, while the closer the distance between the underground structure and the base rock, the more the displacement difference. The occurrence of the declining segment is related to the strength of the effect of these two factors. That the soil exhibits only a linear behaviour under a small-earthquake condition can explain the linear result when the peak acceleration is 0.1g.

Conclusion

This study comprehensively examines the problem of interaction among the elements of a multistructure system through soil. Considerable effort has been exerted to make the model as realistic as possible and to obtain accurate results. A rigorous 3D finite-element model of the structure–soil–structure system is established in

this work to discuss the influence of frame structures on underground structures under different parameters. The influences of four factors – namely, horizontal distance between the frame structures and subway station, length of the pile foundation, orientation of the frame structure and burial depth of the subway station – on the response of the underground structure is discussed in the time domain. An investigation in the time domain is a significant part of the analysis of the seismic behaviour of a multistructure system, which highly complements a frequency-domain analysis. The results are presented in terms of graphs and formulas.

Horizontal distance and burial depth are two key influencing factors given their distinct impacts on the interaction. The interstorey drift ratio response of the subway station is fluctuating, but not monotonous, under different conditions of horizontal distance, and the influence is slight when the distance is sufficiently far. The peak displacement difference increases with an increase in the burial depth of the underground structure, and both variables exhibit a linear growth trend when the acceleration peak of the earthquake motion is $0.1g$. While when the peak acceleration is $0.2g$ or $0.3g$, the peak displacement difference increases with the increase in burial depth overall and declines when the burial depth is 12 m. The remaining parameters – namely, the length of the pile foundation and the orientation of the frame structure – contribute minimally to the response. The influences of these factors can be neglected relative to the first two factors.

Evidently, nearby buildings significantly affect the seismic response of underground structures according to the results of this study. Furthermore, an in-depth exploration on the SSSI problem should be conducted to analyse the seismic behaviour of structures under actual urban spatial arrangement conditions – for example, the seismic behaviour of a school near a subway station.

Acknowledgements

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