STUDY ON THE EARTHQUAKE RESPONSE OF SUBWAY STATION BUILT IN SOFT SITES WITH DIFFERENT THICKNESS OF SOFT SOIL LAYERS

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ABSTRACT :

To research how the thickness of the soft soil layer to affect the earthquake response of subway station, the finite-element method is used to model the nonlinear soil-subway station dynamic interaction when nine soft sites with different thickness of soft soil layers are used as the engineering site of subway station respectively. By the research results given in this paper and others given by author before, it is disadvantageous to the earthquake resistant of subway station when the soft soil layers locate in the lateral foundation of subway station, and it is especially disadvantageous when the soft soil layers are locating in the bottom of lateral foundation of subway station. However, it is advantageous to the earthquake resistant of subway station when the soft soil layers are locating under the foundation. When the soft soil layers are lying in the top of lateral foundation, it is more disadvantageous to the earthquake resistant of subway station with the thickness of soft soil layers becoming larger. However, when the soft soil layers lie in the bottom of lateral foundation or under the foundation of subway station, the thickness of soft soil layer has not accordant effect on the earthquake resistant of subway station.

KEYWORDS: soft soil, subway station, earthquake response

1. INTRODUCTION

The existed earthquake damages of underground structures indicate that its' earthquake resistance ability isn't strong as expected as people. During the strong earthquake taking place, the large deformation of surrounding soft soils maybe make severity damages to the large-scale underground structures such as the subway station. At the present time, researches on the earthquake response of subway station are still staying in the preliminary stage. Many scholars have researched on the earthquake response of tunnels. However, the earthquake response of subway station built in the soft soils hasn't been researched in detail or in system. The existed research results haven't answer how the thickness and depth of soft soil layers to affect the earthquake response of large subway station. Accordingly, how the thickness of soft soil layers lying in different depth to affect the earthquake response of subway station is investigated in this paper by using the finite-elements method.

In this paper, nine soft sites with different depth of soft soil layers and one general site are set as the engineering sites of subway station according to the representative soft site in Nanjing city of China. The earthquake responses of subway stations built in these sites are calculated respectively. The acceleration, displacement and stress responses of subway station built in different sites are compared together. How the thickness of soft soil layers to affect the earthquake response of subway station are analyzed in detail. The research results can be referenced in seismic design of subway station built in soft site.

2. CALCULATION MODEL AND MOTHODS

2.1. Constitutive models of soil and concrete

The visco-plastic model developed by author is used to model the nonlinear dynamic properties of soft soil. Based on the principles of geotechnical plastic mechanics, the incremental visco-plastic memorial nested yield surface model is developed using the nonlinear isotropic and kinematic hardening modulus field theory. At the end of anyone increment, the inverted loading surface, the damaged surface and the initial loading surface witch is tangent with the inside of inverted loading surface are memorized, and dynamic behavior of yield surface is defined by these surfaces. The developed model is implemented in ABAQUS software successfully. The parameters used in this model can be given by tests easily. The relationship of all stress surfaces are shown in Figure 1. this model is developed and introduced in detail by Reference paper.

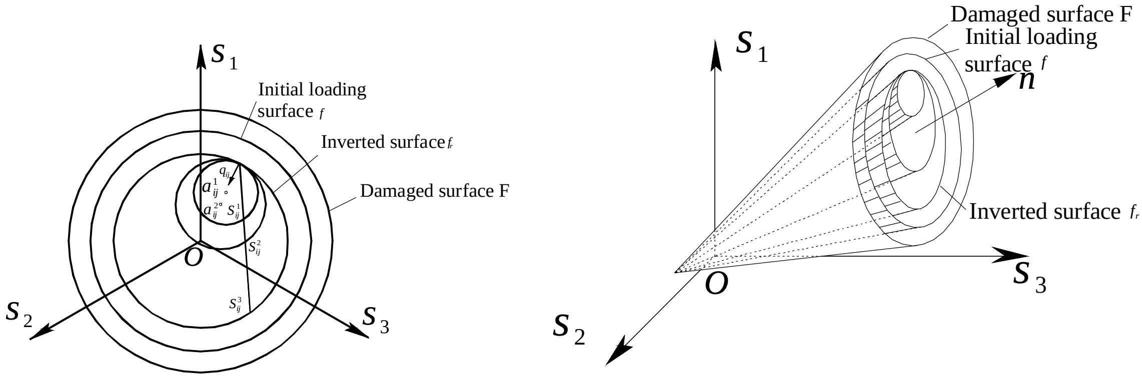
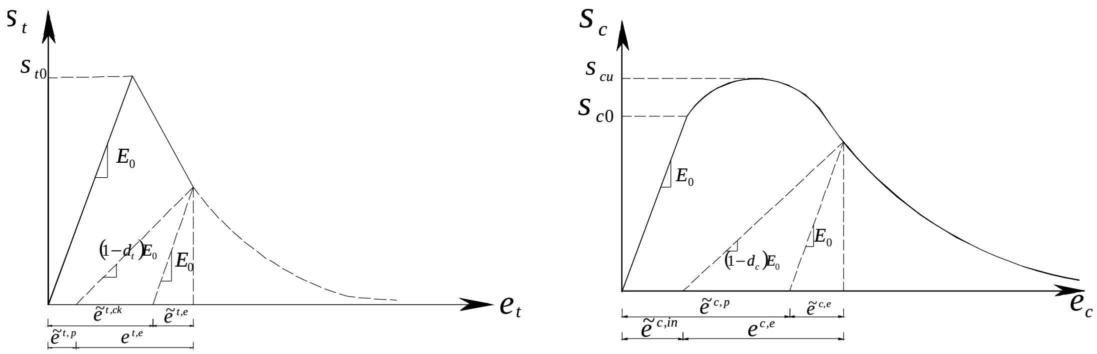


Figure 1 The stress path of yield surface in stress space

The dynamic properties of concrete are simulated by the plastic-damage model presented by Jeeho Lee et al. this model is given by Lubliner et al. based on the fracture energy of concrete firstly, and then it is developed by Jeeho Lee et al. In this model, two damage variables are used to describe the stiffness weakening of concrete when it is damaged by compress and tension stress, respectively. The stress-strain curves are shown in Figure 2.



（a）Compress （b）Tension

Figure 2 Strain-stress curves of concrete

2.2. Soft engineering sites

Table 1 Physical condition of the general site

Parameters / Number of soil layers	Name of soils	Thickness (m)	Referenced shear strain	Shear wave velocity (m/s)	Density (t/m^3)	Cohesive force (kPa)	Internal fraction angle (0)
1～3	Silty clay	7.0	0.00041	160	1.91	15.2	15
4～9	Silty clay	12.49	0.00041	180	1.91	15.2	15
10～15	Silty clay	12.0	0.00041	200	1.91	15.2	15
16～21	Fine sandy	12.0	0.00038	250	2.07	7	16
22～24	clay	6.51	0.0004	300	1.89	20	14

Nine soft sites and one general engineering site are set as the engineering sites of subway station according to the representative soft site in Nanjing city of China. The five soil layers of the general engineering site are shown in Table 1. The soil layers are divided into twenty-four sub-layers shown in Figure 3. The soft soil is muddy silty clay and it's shear wave velocity is 130m/s, and density is 1.81t/m3. The location of soft soil layers in nine soft engineering sites are shown in Table 2. The Poisson's rations of all soils are assumed to be 0.49 in dynamic analysis.

Table 2 Conditions of the soft engineering sites developed

Name of soft sites	**Number of soft soil layers**	**Thickness （m）**	**Location of soft soil layers relative to the subway station**
Soft site Ⅰ	2	2	2m thickness downward from the top of lateral wall
	2、3	4	4m thickness downward from the top of lateral wall
	2、3、4	6	6m thickness downward from the top of lateral wall
Soft site Ⅱ	5、6、7	6	6m thickness upward from the bottom of lateral wall
	6、7	4	4m thickness upward from the bottom of lateral wall
	7	2	2m thickness upward from the bottom of lateral wall
Soft siteⅢ	13	2	From 10m to 12m upward to the bottom of station
	13、14	4	From 10m to 14m upward to the bottom of station
	13、14、15	6	From 10m to 16m upward to the bottom of station

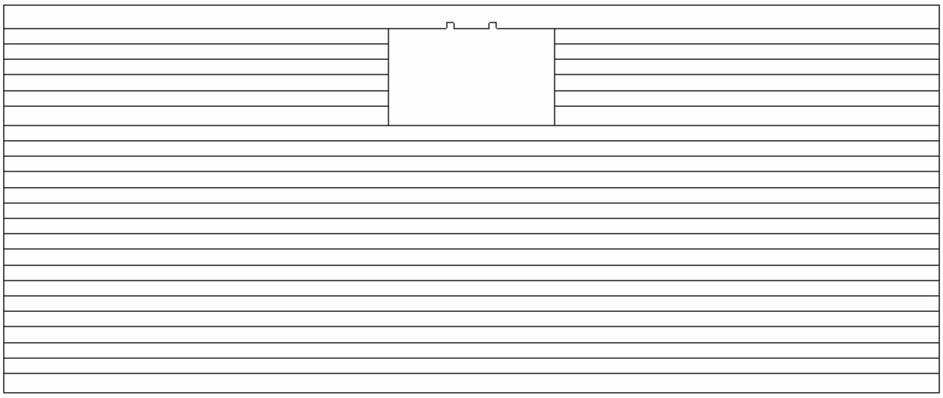


Figure 3 the soil sub-layers of the engineering sites

2.3. Numerical modeling

The subway station has two layers and three spans. The width and height of subway station are 21.2m×12.49m. The thickness of covering earth is 3m. The thicknesses of floor slabs are 0.7m, 0.35m and 0.8m from the top to the bottom of station respectively. The diameter of columns is 0.8m and its' spacing interval is 9.12m.

The 4-nodes reduced integration solid plain strain elements are used to model the soil material and the 4-nodes whole solid integration plain strain elements are used to model the concrete material. The model parameters of C30 concrete are given in Table.3. The lower value for the column takes into consideration that the column is spaced at 9.12 m between axes. The reduced Young's modulus of the column is obtained by performing a 3-D FEM analysis of the structure with the actual dimensions and spacing of the column, and by matching the stiffness of the 3-D structure with a 2-D structure where the column is assumed as a continuous wall with 0.8m thickness.

The boundary conditions of system are set as that the bottom of foundation is constrained in the horizontal and vertical direction and the lateral boundary of foundation is constrained in vertical direction. Based on the researches by Liu Menling et al., when the width of foundation is five times that of structures, the free lateral boundaries can work as energy "sinks" rather than energy "reflectors" in the sense that the energy transmitted to the lateral boundary through the soil media should not be reflected back to the structure. Otherwise, the solution exist in reality. Accordingly, the width of system is set to be 120m in this paper and the thickness of foundation is 50m. The FE meshes are shown in Figure 4.

Table 3 Values of parameters used by the plastic-damage model of concrete

Model parameters	Values	Model parameters	Values
Young's modulus E (MPa)	3.0×10^4	Initial tension yield stress σ_{to} (MPa)	2.9
Poisson's ration ν	0.15	ω_t	0
Density ρ (kg/m^3)	2450	w_c	1
Dilatation angle Ψ (^{0})	36.31	d_c	0
Initial compress yield stress σ_{co} (MPa)	13.0	ξ	0.1
Limited compress stress σ_{cu} (MPa)	24.1		

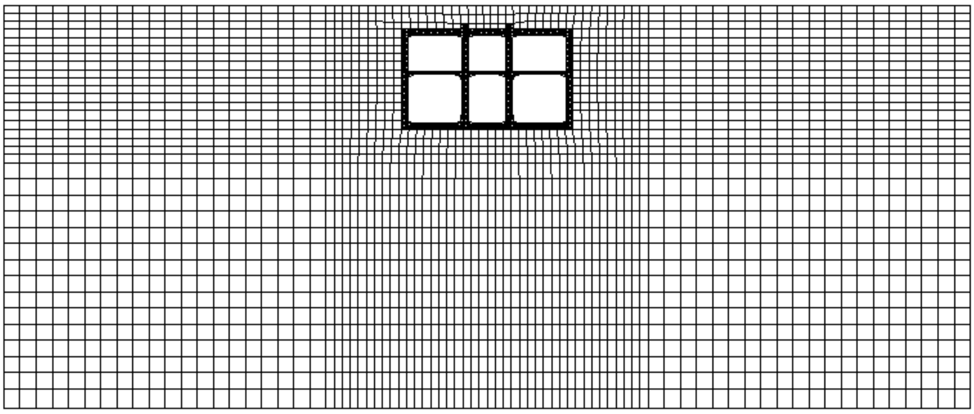


Figure 4 Finite elements of the soil-subway station interaction system

For lacking the strong ground motion records in Nanjing area, in this paper, the time-history of Nanjing artificial earthquake waves are used as the horizontal ground motions inputted from the bedrock. The peak value of this record is 1.14 m/s^2 and the durative time is 30 seconds. The time-history curve of acceleration and it's Fourier spectrum is shown in Figure 5.

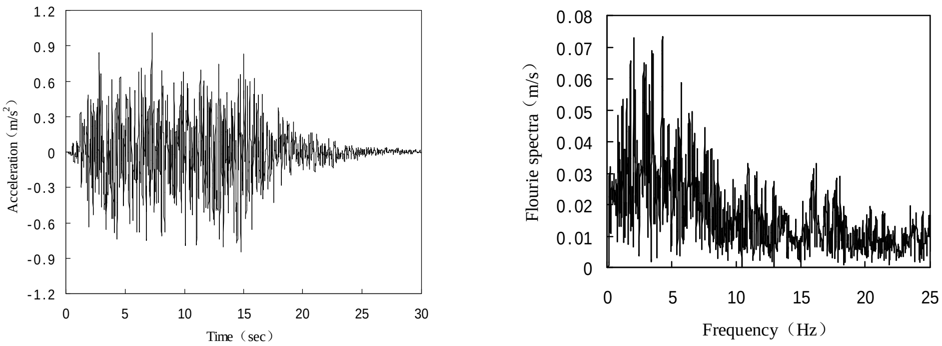


Figure 5 Acceleration history and it's Fourier spectrum of Nanjing artificial earthquake wave

3. RESULTS AND ANALYSIS

3.1. Acceleration response of subway station

According to Table.6 and Figure 4, the acceleration responses of subway station have the following characteristics. Firstly, as far as the same thickness of soft soil layers are concerned, the peak acceleration at the bottom floor of station built in soft site Ⅲ is less than those of station built in soft site Ⅰ and Ⅱ. The peak accelerations at the top floor and middle floor of station built in soft site Ⅱ and Ⅲ are less than those of station built in soft site Ⅰ, respectively. Secondly, the peak accelerations at the top floor of station decrease with the thickness of soft soil layers becoming thicker when subway station built in soft site Ⅰ. However, the peak accelerations at the middle floor of station increase with the thickness of soft soil layers becoming thicker. In a word, the thickness changes of soft soil layer have a little effect on the acceleration response of subway station.

Table 4 the peak accelerations outputted on the floors of subway station

Soft site / Location	General site	Soft site Ⅰ			Soft site Ⅱ			Soft site Ⅲ		
		2m	4m	6m	2m	4m	6m	2m	4m	6m
Top floor (m/s)	0.789	0.810	0.807	0.756	0.711	0.701	0.678	0.712	0.697	0.693
Middle foor (m/s)	0.564	0.580	0.577	0.584	0.491	0.501	0.513	0.480	0.447	0.500
Bottom floor (m/s)	0.959	1.000	1.047	1.000	1.114	0.962	0.972	0.871	0.831	0.778

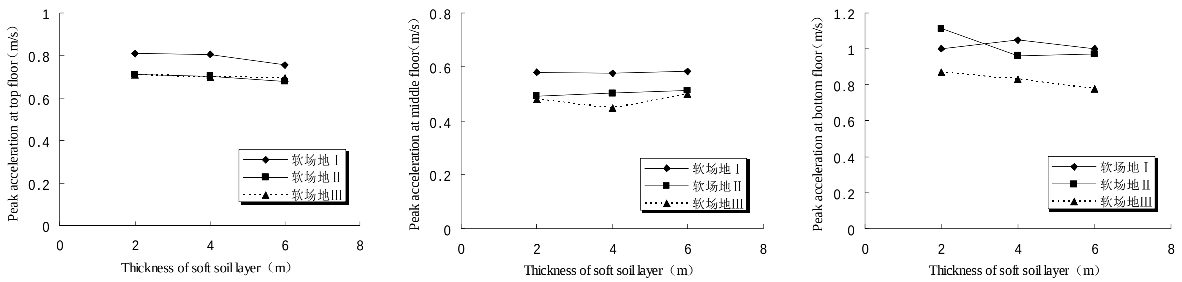


Figure 6 The relations of peak accelerations outputted on the floors versus thickness of soft soil layers

3.2 Lateral displacement response of subway station

The time-histories of relative displacement between the top floor and the bottom floor of subway station are shown in Figure 7. The horizontal displacement curves of lateral wall when the relative displacements reach the peak point are shown in Figure 8. According to Figure 7 and Figure 8, the lateral displacement responses of subway station have the following characteristics.

When the subway station is built in soft site Ⅰ, the peak relative displacements increase with the thickness of soft soil layer become thicker, and these peak relative displacements are all bigger than that of subway station built in general site. The leftward relative peak displacements are also bigger than the rightward relative peak displacements with the same thickness of soft soil layers are concerned. The maximal relative displacement is 10.2mm and it is 2.08 times that of subway station built in general site.

When the subway station is built in soft site Ⅱ, the rightward peak relative displacements increase with the thickness of soft soil layer become thicker, and the leftward peak relative displacement reaches maximal values when the thickness of soft soil layer is 4m. The leftward peak relative displacement is least when the thickness of soft soil layer is 6m. The rightward peak relative displacements are all bigger than the corresponding leftward peak relative displacements with the same thickness of soft soil layers are concerned. The maximal rightward peak relative displacement is 15.3mm and it is 2.34 times that of subway station built in general site.

When the subway station is built in soft site Ⅲ, the rightward peak relative displacements decrease with the thickness of soft soil layer becoming thicker. The maximal peak relative displacement takes place when the subway station swings leftwards with the thickness of soft soil layer being 4m. The rightward peak relative displacements are also bigger than the corresponding leftward peak relative displacement with the same thickness of soft soil layers are concerned.

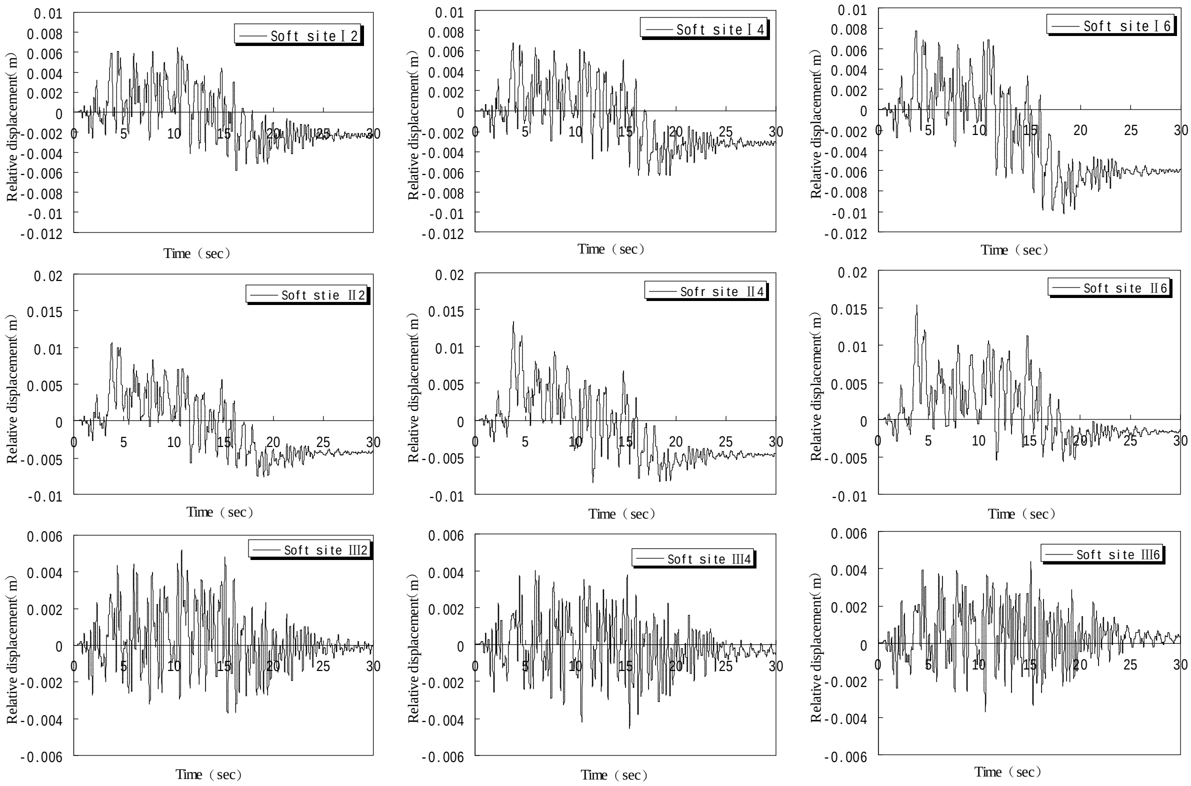
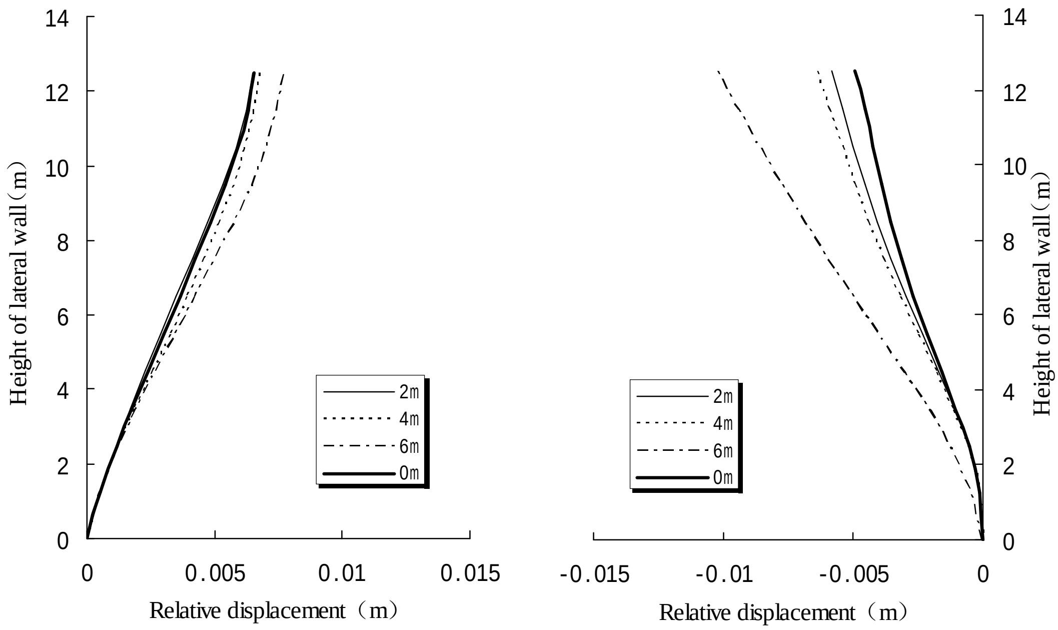


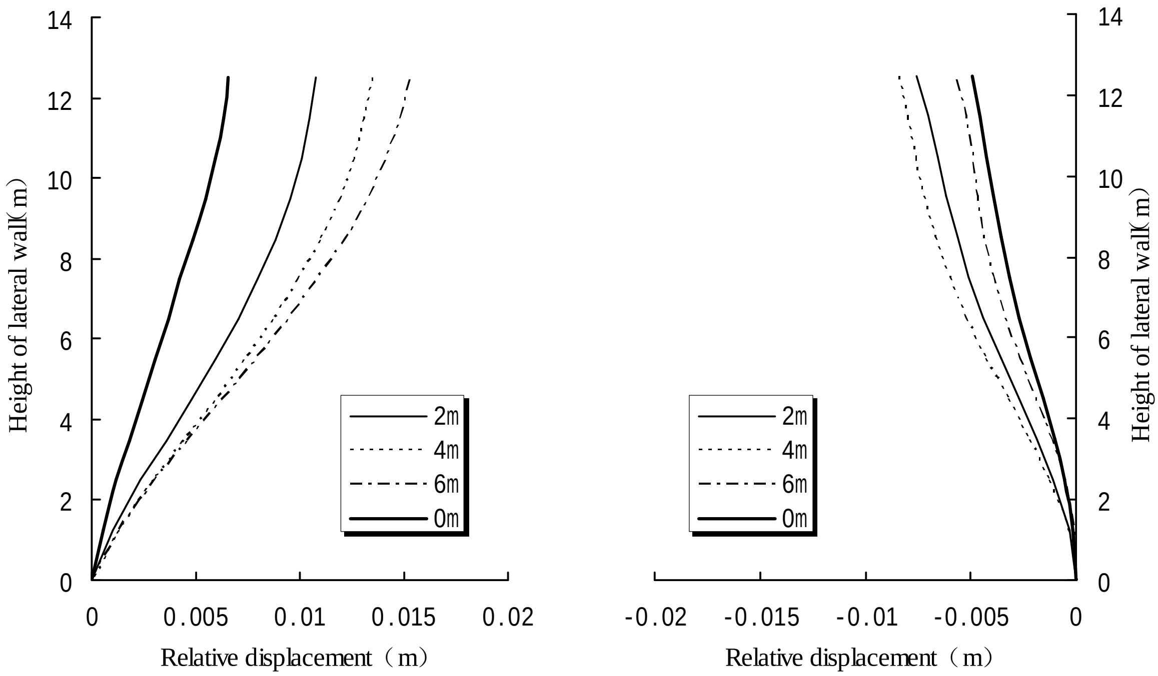
Figure 7 The time histories of relative displacement between top floor and bottom floor of subway station



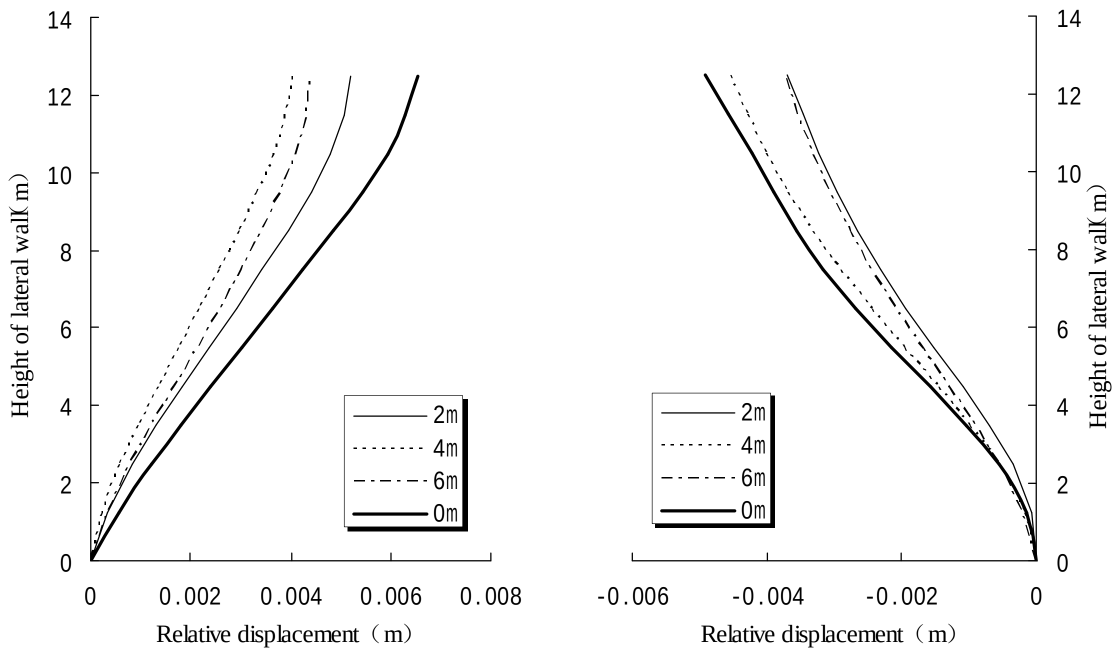
(a) Soft site Ⅰ

When the soft soil located in the lateral foundation of subway station (built in soft site Ⅰ or Ⅱ), the subway station has the leftward permanent remnants horizontal relative displacement. However, when the soft soil layers located in the bottom foundation of subway station (built in soft site Ⅲ), the permanent remnants horizontal relative displacements are close to zero.

When the subway station is built in soft site Ⅰ or Ⅱ, the peak relative displacements are all bigger than the corresponding values when the subway station is built in general site. However, when the subway station is built in soft site Ⅲ, the peak relative displacements are all littler than the corresponding values when the subway station is built in general site.



(b) Soft site Ⅱ



(c) Soft site Ⅲ

Figure 8 The relative displacements distributing curves along the lateral wall of subway station

3.3 Stress response of subway station

In this paper, the stress response coefficient is defined as the ratio of peak stress response at the nodes of subway station built in soft site versus those of subway station built in general site. The relationship of the stress response coefficients and the thickness of soft soil layers at the key nodes of subway station are shown form Figure 10 to Figure 12. The stress response coefficients of subway station have the following characteristics.

When the subway station is built in soft site Ⅰ, the stress response coefficients at the most nodes of lateral wall increase fast when the thickness of soft soil layers change from 4m to 6m. The stress response coefficient at the node 269 is the maximal and is 2.18. When the thickness of soft soil layers change from 2m to 4m, the stress response coefficients at the most nodes have little increasing. The compression stress response coefficients at the nodes of columns increase with the thickness of soft soil layers becoming thicker. The compression stress response coefficients at the nodes of upper columns increase more faster than those of other nodes. The stress response coefficients at the nodes of floors change in the same way as the nodes at the lateral wall. The maximal stress response coefficients at the nodes of floors takes place at the node 2 and it is 1.95.

When the subway station is built in soft site Ⅱ, the stress response coefficients at the most nodes of lateral wall increase fast when the thickness of soft soil layers increase from 2m to 4m. The maximal stress response coefficient at the nodes of lateral wall is 3.47. When the thickness of soft soil layers change from 4m to 6m, the stress response coefficients at the nodes of lateral wall decrease except at the node 190. The stress response coefficients at the other nodes of subway station change in the same way as the nodes of subway station when the subway station built in soft site Ⅰ.

When the subway station is built in soft site Ⅲ, the stress response coefficients at the most nodes of subway station are less than 1 except to the nodes 190, 1 and 2. The stress response coefficients at the nodes 190, 1 and 2 increase with the thickness of soft soil layers becoming thicker.

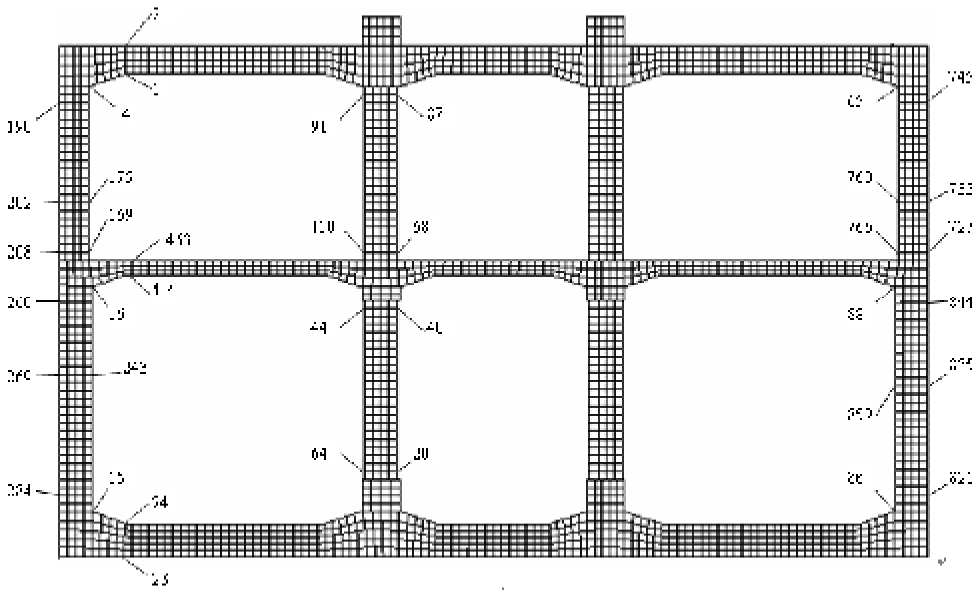


Figure 9 The nodes' locations which stress responses analyzed

Table 5 The peck stresses in different finite-element nodes of subway station（**Unit：MPa**）

Lateral walls			**Middle columns**			**Floors**		
Nodes	**Tension**	**Compress**	**Nodes**	**Tension**	**Compress**	**Nodes**	**Tension**	**Compress**
190	0.462	1.568	91	0.126	0.457	1	1.948	0.518
202	0.487	0.568	110	0.126	0.382	2	0.398	1.509
208	0.676	0.360	44	0.127	0.647	463	0.954	2.047
260	0.681	0.482	64	0.119	0.730	414	1.888	1.346
269	0.332	0.414				24	2.271	2.094
284	1.233	1.697				23	1.558	1.805

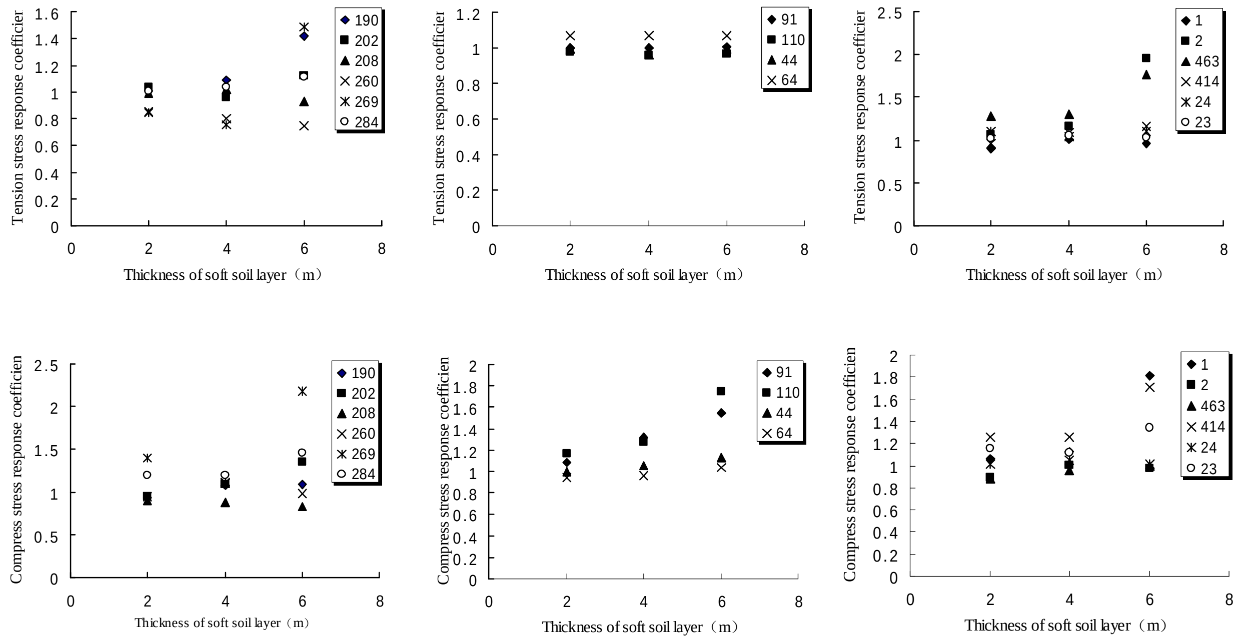


Figure 9 The stress response coefficients of subway station with different thickness of soft soil layers in soft site No. Ⅰ

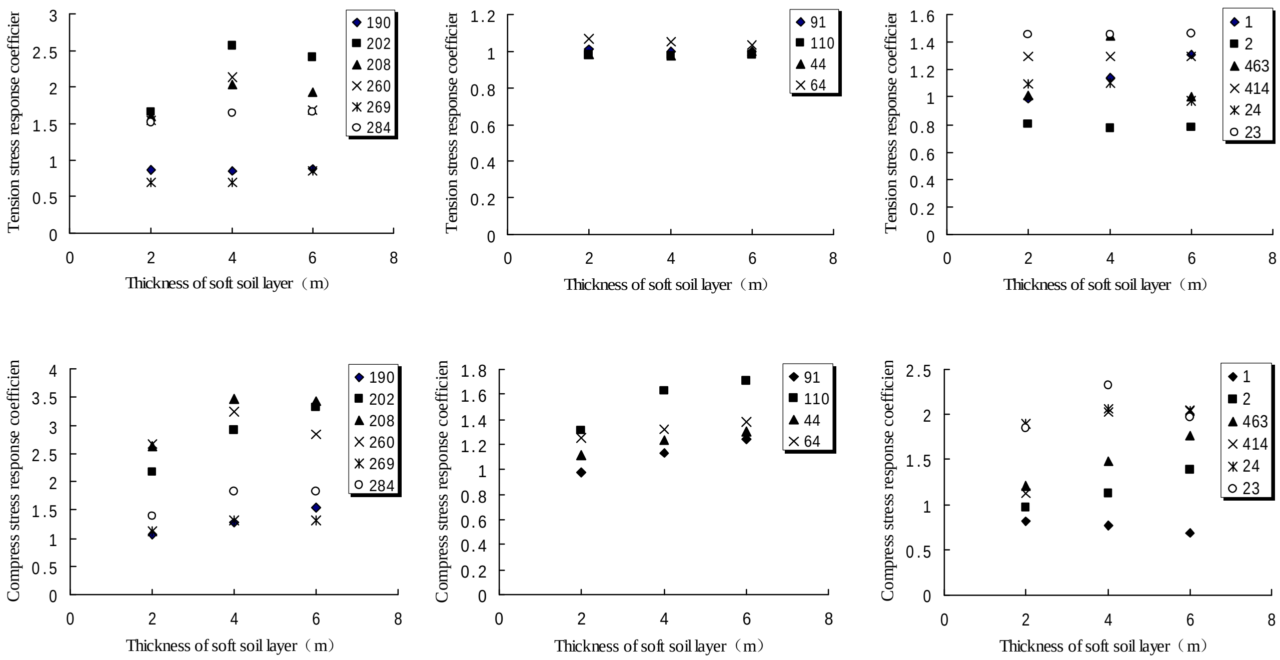


Figure 10 The stress response coefficients of subway station with different thickness of soft soil layers in soft site No. Ⅱ

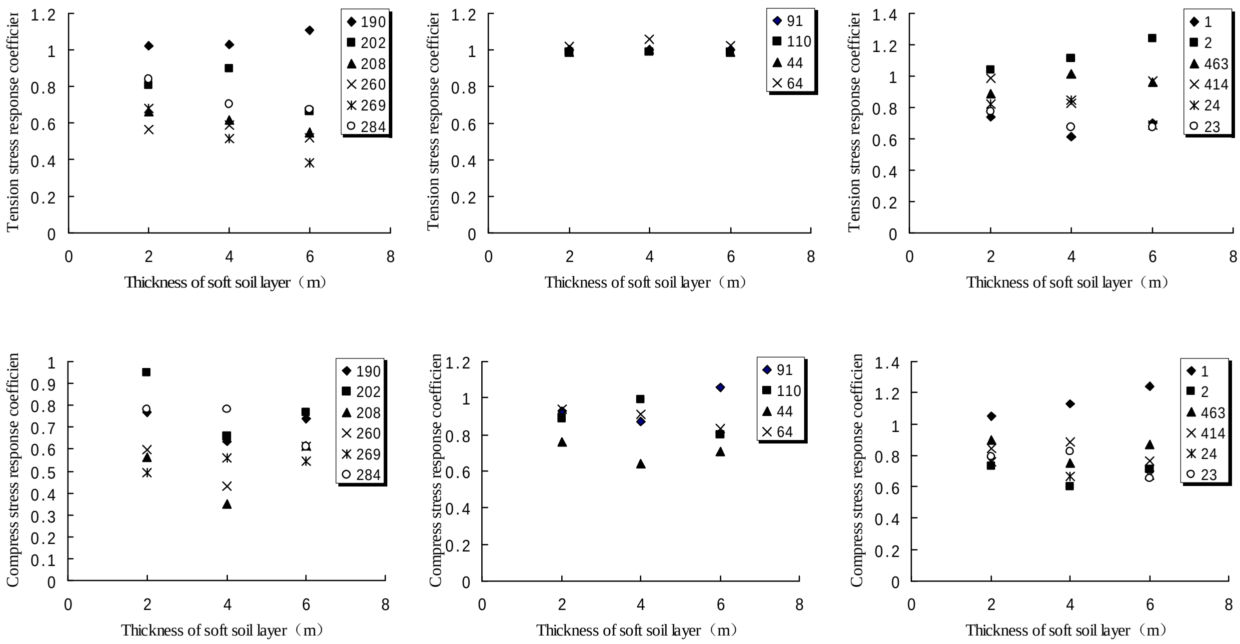


Figure 11 The stress response coefficients of subway station with different thickness of soft soil layers in soft site No.III

4. SUMMARIZATION

In this paper and the paper named 'Study on the earthquake responses of subway station with the large lateral displacement of soft soil', the earthquake responses of subway station built in 12 soft sites and one general site are analyzed in system. As a whole, when the soft soil layers located in the lateral foundation of subway station, it is disadvantage to the seismic resistant of subway station, and it is disadvantage especially when the soft soil layers located in the lateral bottom foundation of subway station. However, it is advantage to the seismic resistant of subway station when the soft soil layers located under the subway station. In addition, when the soft soil layers are lying in the bottom of lateral foundation or under the foundation of subway station, the thickness of soft soil layers have not accordant effects on the earthquake resistant of subway station.

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