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Analysis of the Response Law of Station Buried Depth Change to Subway Station Under Vibration Load

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Abstract: In the period of rapid development of urban rail transit, the traditional transportation hub has become increasingly unable to meet the needs of people 's travel due to the lack of rationality and efficiency of land use, the monotonous structure and other reasons, resulting in a series of new three-dimensional transportation hub. The Huangmugang comprehensive transportation hub in Shenzhen is a complex four-story underground station with different spans. The station adopts a large-diameter and large-angle V-column structure system. In this paper, a simplified seismic analysis method suitable for the V-pillar structure of subway station is proposed, and the two-dimensional finite element model and dynamic time history analysis of subway station are completed in combination with practical engineering cases. The influence of buried depth change of station on the response law of subway station is studied. The seismic response results of station under three different buried depths are analyzed, and the stress and deformation law of key components such as V-pillar, side wall and station floor of station structure are compared and analyzed.The main conclusions are as follows : with the increase of the buried depth of the station, the constraint effect of the surrounding soil on the station structure is obviously enhanced, which is manifested by the increase of the constraint effect of the soil on the side wall of the station and the decrease of the displacement of the side wall. However, with the further increase of the buried depth of the station, the constraint effect of the surrounding soil on the station tends to be stable. At the same time, due to the increase of the thickness of the overlying soil, the self-weight stress transmitted by the soil of the station increases, which makes the deformation of the side wall of the station increase.

Keywords: Subway stations; V-column structure; Earthquake response rule; Station buried depth; Elastoplastic analysis；Numerical simulation

China is a country with serious earthquake disasters due to its high frequency and intensity of seismic activity. In the period of rapid development of urban rail transit, new subway stations have developed toward comprehensiveness, large scale and complexity. The damage of underground structures under strong earthquakes has attracted widespread attention. In recent years, scholars at home and abroad have proposed a variety of theoretical analysis methods for the seismic design of underground structures. The Japanese scholar Omori[1], who first proposed the use of static theory to carry out the seismic design of underground structures, introduced the application of elastic mechanics theory to underground structures to determine the stress and strain state of underground structures. Currently, with the rapid development of computer technology, an increasing number of scholars are using numerical analysis methods to study the seismic resistance of structures[2-4]. Numerical simulations can consider inhomogeneous media and complex boundary conditions[5-6] and simulate discontinuous contact problems such as voids, slips and dislocations between soil and structures[7]. To adapt to the development of underground engineering, on the basis of theory, numerical analyses and earthquake damage summaries, domestic and foreign scholars have further made some assumptions and simplifications on seismic analysis methods for underground structures and proposed a series of practical simplified seismic analysis methods for underground structures. However, considering the complex and diverse forms of subway stations, appropriate seismic analysis methods should be selected for different subway stations. Taking a subway station in Xi'an as an example, Wang[8] established a two-dimensional subway station model based on ABAQUS software, compared and analyzed the stress and deformation laws of the station under different seismic waves, and determined the seismic weak parts of the station type. Taking a shallow two-story double-span subway station in Beijing as an example, Xu Zigang[9] studied the influence of the diaphragm wall of the subway station on the dynamic response of the station under the action of horizontal-vertical two-way ground motion.In summary, the subway station form is complex and diverse[10], for different stations we should choose the appropriate seismic analysis method. At present, there are very few seismic damage data about special-shaped columns at home and abroad. This paper will systematically study the stress and deformation characteristics of reinforced concrete V-shaped column structure system, and clarify its seismic performance and engineering applicability.

In this paper, a simplified seismic analysis method suitable for V-column structure of subway station is determined, and the seismic performance of subway station is studied by this method. This paper uses the MPC (Multi-point Constraints)[11-13]node degree of freedom coupling constraint function. The overall evolution of subway station under ground motion is studied. The dynamic response and elastoplastic damage of subway station are analyzed, and the seismic weak components of station structure under ground motion are determined. The influence of the change of the buried depth of the station on the seismic response of the station is studied. The seismic results of the station under three different buried depths are analyzed. The stress and deformation rules of the key components such as the V-shaped column, the side wall and the station floor of the station structure are compared.

1 Analysis Method

1.1 Model Overview

The subway station model is based on the actual engineering background of the Shenzhen Huangmugang comprehensive transportation hub project. The standard section of the station is buried at a depth of 2 m. The heights of the layers from top to bottom are 11.5 m, 8 m, 8 m and 8.5 m, respectively. The width of the negative first and negative second floors is 54 m, and the width of the negative third and negative fourth floors is 31.2 m. The main vertical bearing member of the station structure is the V-pillar, which is distributed along the longitudinal direction of the station, as shown in Figure 1. The angle between the inclination angle of the inclined column of the standard section of the station and the direction of the lead hammer is 10.931 degrees. The seismic intensity of the area where the station is located is VII degrees. The peak acceleration of the design ground motion is 0.1 g, and the seismic fortification category of the main structure is the key fortification category.

Fig. 1 Cross-Section of Comprehensive Transportation Hub

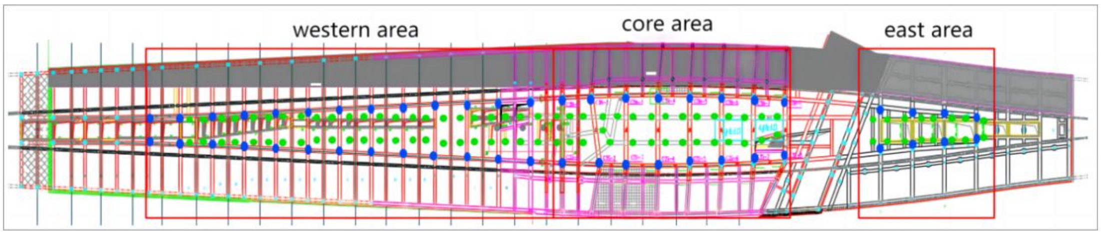


Fig. 2 Layout Plan of Inclined Columns of Comprehensive Transportation Hub

Based on the actual engineering background of the Shenzhen Huangmugang comprehensive transportation hub project, the standard section of the station is buried at a depth of 2 m. The heights of the layers from top to bottom are 11.5 m, 8 m, 8 m and 8.5 m, respectively. The width of the negative first and negative second floors is 54 m, and the width of the negative third and negative fourth floors is 31.2 m. The main vertical load-bearing component of the station structure is the V-pillar, which is distributed along the longitudinal direction of the station, as shown in Figure 3.

The inclined angle between the inclined column of the standard section of the station and the lead hammer direction is 10.931 degrees. Column V of the station structure adopts C60 concrete, and the other station members adopt C40 concrete. According to the "Seismic Design Standard for Underground Structures" (GBT51336-2018), when performing time-history analysis of underground structures, the soil boundary of the numerical model should not be less than 3 times the maximum size of the single side of the structure. Therefore, after simplifying the actual structure, the finite element model shown in Figure 3 is established, with a width of 300 m and a height of 200 m.

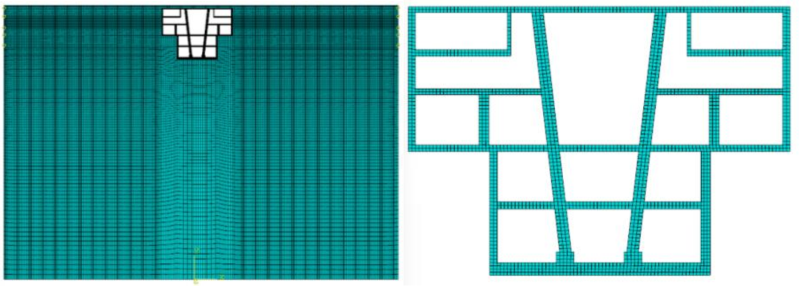


Fig. 3 Element model of the station structure

1.2 Material parameters and ground motion parameters

According to field engineering investigations and corresponding engineering data, the main components of the soil around subway stations are clay soil, gravel and gravel, which are relatively unstable soils. The area where the subway station is located is mainly covered by the residual soil of granite and its fully weathered and strongly weathered layers, and there is uneven weathering in the weathered rock of granite.

The site soil layers with similar physical and mechanical properties are merged and simplified. The strata where the station is located are plain fill, silty clay, gravel clay, fully weathered Huanggang rock, soil-like strongly weathered granite, and moderately weathered granite. The Mohr–Coulomb constitutive model is used for each layer of soil. In the dynamic analysis, the initial dynamic elastic modulus of the soil is used to determine the shear wave velocity and dynamic Poisson's ratio of each layer of soil in the geotechnical investigation report, and the specific parameters are shown in Table 1.

Table 1 Model Material Parameters Table

Material type	Elastic modulus (MPa)	Poisson ratio	Density (kg/m^3)	Shear modulus (MPa)	Shear wave velocity (m/s)	Angle of friction
Plain fill	22.3	0.3	1900	8.58	108.34	25
Silty clay	26.2	0.3	1800	10.08	120.65	20
Gravel cohesive soil	42.4	0.3	1870	16.31	150.58	21
Completely decomposed granite	48	0.35	2050	17.78	161.08	24
Highly weathered granite	131.2	0.35	2240	52.48	267.03	26
Moderately weathered granite	178	0.35	2600	65.93	269.65	40.5
Station structure	32500	0.2	2400			
Station V-pillar structure	42900	0.3	2400			

The plastic damage constitutive model of concrete adopts the plastic dynamic damage (CDP) model. The model uses two variables, tensile damage and compressive damage factor, to describe the stiffness attenuation law of concrete after tension and compression, respectively. Using the MPC node degree of freedom coupling constraint function, the boundary nodes of the subway station model are bound to make the nodes move uniformly.

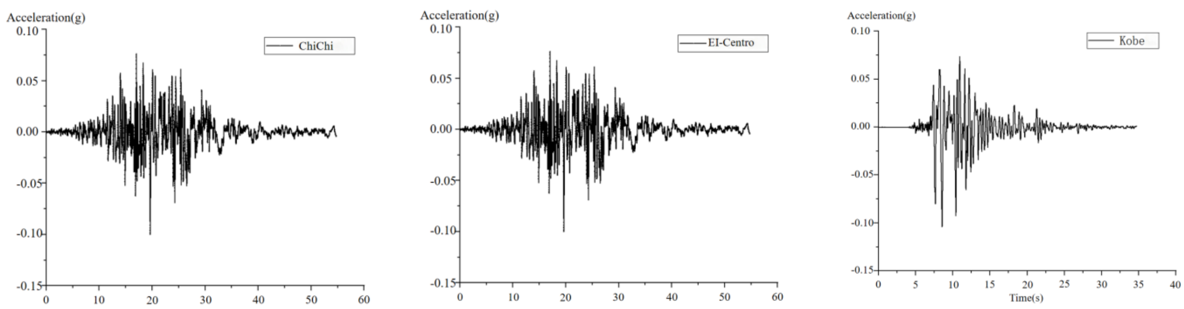
Through the vibration input method, the dynamic acceleration generated by ground motion is directly applied to each node of the station structure in the form of an inertial force to simulate the vibration effect of each particle. The contact between the soil and the station structure needs to be set up, in which the normal contact adopts the 'hard' contact in ABAQUS, allowing separation between the two; the tangential contact is simulated by the penalty function in ABAQUS, and the friction coefficient is set to 0.4. The specific analysis process is as follows: First, the stress state of the unit under the self-weight load of the soil-station structure system is calculated, and the self-weight stress field of the soil is obtained. Then, dynamic implicit analysis is carried out, and the analysis step length is consistent with the seismic loading time.

At the same time, the element stress state calculated by the static analysis is input in the form of a prestressed field. Finally, the acceleration time history is input by means of vibration so that the soil-station structure generates an inertia force to simulate the vibration effect of each particle, and the dynamic time history analysis of the subway station is completed.

1.3 Seismic wave input selection

At present, the amplitude modulation method of ground motion records is mainly divided into equal step size and unequal step size. This paper refers to the research experience of relevant scholars[15] to select each ground motion acceleration according to the proportional amplitude modulation. Based on three real ground motion records Chi-Chi wave, EI-Centro wave and Kobe wave, a horizontal seismic wave with a peak acceleration of 0.1 g is constructed.

Based on the research experience of relevant scholars[14], this paper adjusts the acceleration of each selected ground motion according to the proportion. Based on the three real ground motion records, the Chi-Chi wave, the El-Centro wave and the Kobe wave, a horizontal seismic wave is constructed when the peak acceleration of the design ground motion is 0.1 g.



(a) Tectonic Chi-Chi wave **(b) Tectonic EI-Centro wave** **(c) Tectonic Kobe wave**

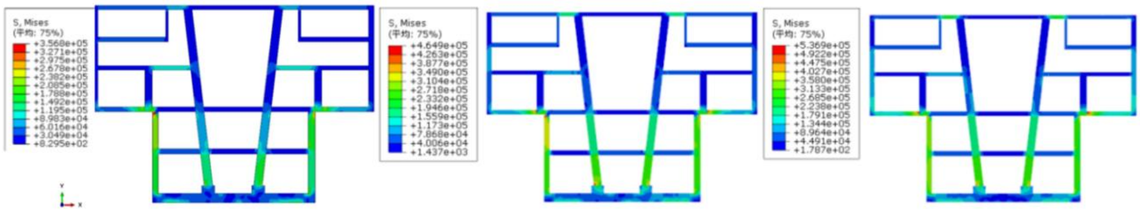
Fig. 4 Seismic acceleration-time history curves

2 Analysis of the response law of different buried depths to subway stations under ground motion

The buried depth of the station refers to the height from the roof of the station to the ground. The energy released by the earthquake propagates in the earth's interior and reaches the surface in the form of elastic waves, and the influence on the underground structure will be different due to the different buried depths. In addition, the buried depth of the station will also affect the dynamic characteristics of the underground structure. With the increase of the buried depth, the natural vibration period of the underground structure may change, thus changing the response of the structure to the seismic wave. At the same time, considering that the interaction between the subway station and the surrounding soil will also change with the change of the buried depth of the station, thus affecting the dynamic response law of the subway station under the action of earthquake. Therefore, the buried depth of the station is an important factor affecting the seismic response of underground structures.

In order to further study the response and vulnerability of subway station structure under different buried depth conditions, three different working conditions of buried depth of 2 m, 12 m and 22 m were selected for specific analysis. Through the simulation and analysis of the subway station structure under different buried depths, the stress state, response characteristics and potential damage risk of the subway station under different buried depths are more comprehensively understood, which provides a more scientific basis for the seismic design and safety protection of the subway station.

2.1 Comparative analysis of station structure stress

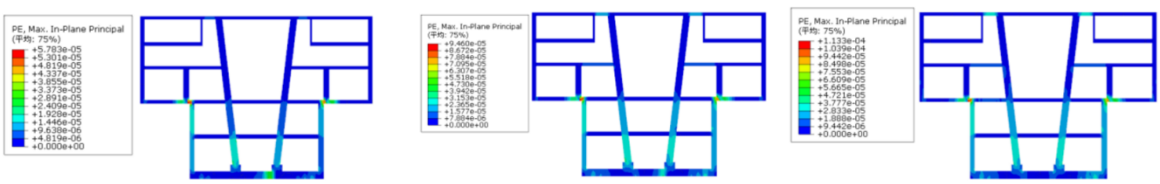


(a)2 m of buried depth Stress **(b)12 m of buried depth Stress** **(c)22 m of buried depth Stress**

Fig. 5 Stress Cloud Diagram of Stations Buried at Different Station Depths

It can be seen from Fig.5 that with the increase of the buried depth of the station, the roof of the station increases significantly due to the increase of the thickness of the overlying soil layer. The maximum equivalent stress of the V-pillar structure of the subway station still appears at the junction of the middle and lower part of the side wall of the station and the negative second floor. Among them, there is a more obvious force concentration at the junction of the side wall and the negative second floor. The stress at the junction of the side wall and the negative second floor is slightly larger than that at the junction of the side wall and the short column. The stress of the station structure itself also increases, and the buried depth has a great influence on the peak stress of the station structure. The buried depth of the station increases by ten meters, and the peak stress of the structure increases by about thirty percent.

2.2 Comparative analysis of plastic strain of station structure



(a)2 m of buried depth Deformation **(b)12 m of buried depthDeformation** **(c)22 m of buried depth Deformation**

Fig. 6 Deformation Cloud Map of Stations Buried at Different Station Depths

It can be seen from Fig.6 that with the increase of the buried depth of the subway station structure, the load acting on the roof of the structure increases rapidly. However, unlike the analysis of the rectangular subway station structure in other studies, that is, with the increase of the buried depth, the lateral restraint effect of the surrounding soil layer is not obvious, resulting in the V-pillar structure on the upper part of the station to bear a large axial force, resulting in the strain on the upper part of the V-pillar of the subway station structure greater than the strain on the lower part. In the V-pillar structure of the station, with the increase of the buried depth of the station, the upper deformation of the V-pillar structure is always smaller than the bottom deformation. At the same time, with the increase of buried depth, in the analysis of V-shaped column in the third chapter, it is found that the plastic strain value of the measuring point on the forward inclined side is obviously smaller than that on the backward inclined side, and the more obvious along the V-shaped column downward, the law gradually weakens with the increase of the buried depth of the station. The overall change of the upper part of the station side wall is small. With the change of buried depth, the peak value of plastic strain is always located at the junction of the left wall and the negative second floor slab and the left short column, which is in good agreement with the stress concentration shown in the stress cloud map of the station. Therefore, the bottom of the negative first floor wall and the top of the negative second floor wall are the weak parts of earthquake resistance.

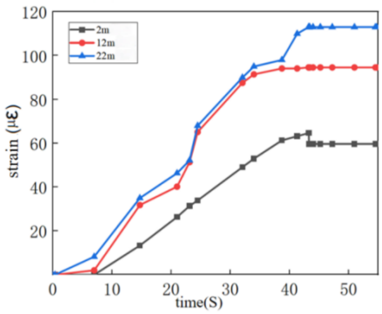
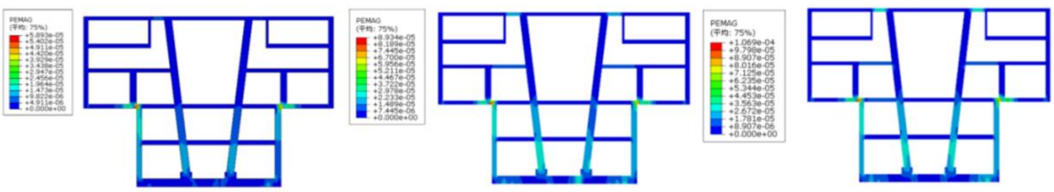


Fig.7 Peak Plastic Strain Diagram of Stations Buried at Different Station Depths

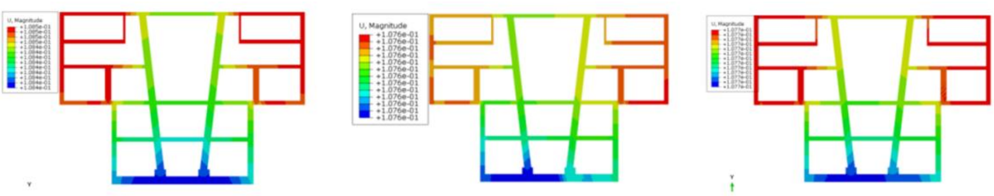
It can be seen from Fig.7 that as the buried depth of the station increases, the peak plastic strain of the station structure also increases. The station enters the plastic stage earlier from the elastic stage. The buried depth has a great influence on the peak plastic strain of the station structure. The buried depth of the station increases by ten meters, and the peak plastic strain increases by about 50%.



(a)2 m of buried depth Plastic Damage (b)12 m of buried depth Plastic Damage (c)22 m of buried depth Plastic Damage

Fig. 8 Plastic Damage Cloud Map of Stations Buried at Different Station Depths

It can be seen from Fig.8 that with the increase of the buried depth of the subway station structure, the plastic damage of the overall structure of the station also increases. The concrete manifestation is that with the increase of the buried depth of the station, the plastic damage of the station roof increases obviously; the plastic damage at the bottom of the side wall is significantly greater than that at the upper part of the side wall. The plastic damage at the junction of the bottom of the V-pillar and the bottom plate is also significantly greater than that of the surrounding parts.



(a)2 m of buried depth Displacement cloud (b)12 m of buried depth Displacement cloud (c)22 m of buried depth Displacement cloud

Fig. 9 Maximum Displacement Cloud Map of Station Structure With Different Station Depth

It can be seen from Fig.9 that with the increase of the buried depth of the station, the maximum displacement of the overall structure of the station decreases first and then increases. At first, with the increase of the buried depth of the station, the constraint effect of the surrounding soil on the station structure is obviously enhanced, which is manifested as the constraint effect of the soil on the side wall of the station increases, and the displacement of the side wall decreases obviously. However, with the further increase of the buried depth of the station, the constraint effect of the surrounding soil on the station tends to be stable. At the same time, due to the increase of the thickness of the overlying soil, the self-weight stress transmitted by the soil of the station increases, which makes the deformation of the side wall of the station increase. In addition, due to the constraint of the surrounding soil, the deformation of the side wall, V-shaped column and floor of the station is constrained by the surrounding soil in the vertical deformation direction. The deformation cloud map of the station is mainly the change of horizontal deformation. During the earthquake, the overall structure of the station has obvious horizontal displacement, and the whole is inclined to one side. In all floors, the negative second floor has the largest horizontal displacement.

2.3 Comparative analysis of inter-story displacement angle of station structure

In the process of seismic design, we generally follow the principle that when the local substructure is subjected to a small intensity earthquake, the structural damage should be kept within an acceptable range. "Standard for seismic design of underground structures" This code adds the fortification level of extremely rare ground motion, and stipulates that special fortification underground structures need to meet the higher fortification goal of "no damage under medium earthquake, minor repair under major earthquake, and major repair under great earthquake". We should pay more attention to the deformation and displacement of the structure to ensure its safety performance under earthquake.

The inter-story displacement angle is a key parameter to determine the seismic capacity of the structure, and it is the ratio of the maximum horizontal displacement between floors to the height of the floor. The inter-story displacement angle is not affected by the height of the floor and reflects the degree of deformation of different floors of the station. It can be related to the current seismic design code and can be well equivalent to other parameters.

Table 2 The maximum inter-story displacement angle of stations with different buried depths of stations

Buried depth (m)	Interlayer displacement angle (rad)
2	1.548/1000
12	1.858/1000
22	2.064/1000

It can be seen from Table 2 that with the increase of the buried depth of the station, the maximum inter-story displacement angle of the station decreases first and then increases. At first, when the buried depth of the station is two meters, the maximum inter-story displacement angle of the station is 2.064/1000. According to the performance description of the underground structure in the 'Code for Seismic Design of Buildings', the subway station structure is destroyed under the action of ground motion. However, after timely repair work, it is expected that the station can quickly restore its normal use function in a short period of time. Some structural components of the station have entered the elastoplastic working stage, especially the V-pillar structure and the negative second floor of the station are in the plastic working state.

However, local damage will not have a significant impact on the overall performance of the station. The station has the ability to quickly return to normal working conditions, and the entire structural system remains in an elastic working state. In addition, with the increase of the buried depth of the station, the constraint effect of the surrounding soil on the station structure is also significantly enhanced, which further enhances the stability of the station structure. It is helpful to improve the seismic performance of the station.

The maximum inter-story displacement angle of the station reaches 1.548/1000, and the station structure can still maintain good integrity after the earthquake, without serious damage, and can maintain normal use function. The whole structure is in the elastic working stage. From the perspective of seismic analysis, the structure at this time can be regarded as an elastic system and has good seismic performance. The structure of the subway station can maintain good integrity, and even if there is slight damage, the traffic function will not be interrupted.

3 Conclusions

In this paper, a simplified seismic analysis method suitable for V-column structure of subway station is determined, and the seismic performance of subway station is studied by this method. The main conclusions are as follows:

(1) With the increase of the buried depth of the structure, the peak stress of the station roof increases significantly due to the increase of the thickness of the overlying soil layer, and the maximum equivalent stress of the V-column structure of the subway station still appears at the junction of the middle and lower part of the station side wall and the negative second floor slab.

(2) For every ten meters increase in the buried depth of the station, the peak stress of the structure increases by about thirty percent, which will make the whole structure of the station enter the elastoplastic working state faster under the action of ground motion.

(3) With the increase of the buried depth of the station, the constraint effect of the surrounding soil on the station structure is obviously enhanced, and the displacement of the side wall is obviously reduced; however, with the further increase of the buried depth of the station, the constraint effect of the surrounding soil on the station tends to be stable.

(4) The self-weight stress transmitted by the soil of the station increases, which makes the deformation of the side wall of the station increase, so with the increase of the buried depth of the station, the maximum displacement of the whole structure of the station decreases first and then increases.

(5) Moderately increasing the buried depth of the station is of great significance for improving the seismic performance of the subway station structure. However, when the buried depth of the station is too large, it is not only unable to continue to enhance the seismic performance of the subway station structure, but may weaken its seismic capacity. Therefore, in the actual engineering practice, it is necessary to carefully consider the buried depth of the station to achieve the best seismic effect.

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