Seismic Performance Analysis of Metro Station

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Abstract. In this paper, the Qingping Slope station in Nanning is taken as the research object, in the light of seismic performance of underground station structure, considering the soil-structure dynamic interaction, using a finite element software, and based on reasonable simplification and simplification conditions, the three-dimensional model of the whole station which includes soil, station structure and pile foundation is established, then the seismic analysis is carried out and the dynamic response value of different transcendental probabilities and different seismic waves is obtained. Through analysis, it is found that the bending moment of the connection between the column and the roof and the floor of the station is larger; and for different seismic waves with the same peak value, the dynamic response of the station structure is obviously different, but the corresponding variation trends of the structure are consistent; because the constraints of the junction between the two ends of the tunnel are partly weaker than the middle, the bending moment of the column is larger; at the same time, it can be aware that maintaining the symmetry of the cross section is beneficial to the improvement of the seismic performance of the subway station structure. The research results can be provided to similar seismic analysis of underground engineering structure as useful reference and suggestions.

1. Introduction
With the improvement of engineering requirements[1], the structure of subway stations is becoming more and more complicated, large-scaled, and the diversity of surrounding soil environment. When seismic design is carried out, there are mainly problems below that need to be solved [2-3]: ① The dynamic characteristics of the metro station structure are affected by the surrounding soil, and at the same time affect the surrounding soil. Therefore, it is necessary to consider the interaction between the soil and the station structure; ② Because the seismic waves have different propagation speeds in different soil layers and when the structure of the station is used, different combinations of working conditions need to be considered, so the calculation workload is large; ③ The span of the metro station tends to be large, and the spatial wave and time effect exist. When the seismic wave are transmitted, the structure of the station structure is complicated. ④ The difference among the station structure and the soil’s specific gravity, elastic modulus, stiffness, etc., which makes the input of seismic waves difficult to determine; ⑤ the depth of the station structure, the surrounding terrain and the nature of the surrounding soil also have a great impact on the seismic performance analysis. These influencing factors make the seismic analysis of the subway underground station structure much more complicated than the general ground structure. In order to evaluate the performance of subway underground stations and summarize the characteristics of dynamic response during earthquake action[4], it is necessary to carry
out a three-dimensional space model considering soil-structure interaction, carrying out dynamic
elastoplastic response analysis of metro station structure.

2. Project Overview
Nanning Subway Qingping Slope Station is a two-storey island-style station. The station has four
entrances and exits with a total length of 207.6 meters and a standard section width of 19.7 meters. From
the top to the bottom of the station, the geotechnical soils are: under-compacted fill, hard-plastic-hard
viscous soil layer, soft plastic-plasticized clay soil and medium-weathered limestone stratum. The meso-
weathered limestone exposed by the base excavation has a hard rock; at the same time, the karst water
has bearing capacity; at the interface of the rock and soil, affected by the groundwater, the soil is partially
soft and plastic, and it is easy to slide along the soil-rock interface. The karst is moderately developed,
the height of the cave is about 0.6-7.0 meters, and the anti-floating level is seventy-six meters. It is class
II site category and seven degree seismic fortification intensity.

3. Soil-structure dynamic interaction research
Due to the existence of soil around the structure of the metro station, the dynamic characteristics such
as stiffness and damping of the overall structural system are changed, which in turn causes changes in
the input ground motion characteristics. When the surrounding soil and the metro station structure are
integrated as a whole to perform the graph-structure interaction analysis[5], it is necessary to study many
nonlinear problems such as large deformation, contact and discontinuity[6].

3.1. Dynamic equation
For the nonlinear analysis of soil-structure interaction in metro stations[7], soil and structure as two
different material units need to share nodes on the contact surface, so that the deformation compatibility
and dynamic balance conditions can be automatically satisfied. The corresponding dynamic equation
is[8]:

\[
\begin{bmatrix}
M_m & 0 \\
0 & M_s
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_m \\
\ddot{u}_s
\end{bmatrix}
+ \begin{bmatrix}
C_m & C_ms \\
C_sm & C_s
\end{bmatrix}
\begin{bmatrix}
\dot{u}_m \\
\dot{u}_s
\end{bmatrix}
+ \begin{bmatrix}
K_m & K_ms \\
K_sm & K_s
\end{bmatrix}
\begin{bmatrix}
u_m \\
\nu_s
\end{bmatrix}
= \begin{bmatrix}
F_m \\
F_s
\end{bmatrix}
\]  

(1)

In the formula, M is the mass matrix, C is the damping matrix, K is the stiffness matrix, F is the
external load, subscript s is the soil parameter, and subscript m is the structural parameter of the metro
station.

Equation (1) can be solved by stepwise integration, and the value of structural dynamic response
from the beginning to the end of the earthquake is studied, which belongs to simulation analysis.

3.2. Selection of seismic waves
The dynamic response of the structure under ground motion is closely related to its own dynamic
characteristics and the amplitude, spectral characteristics and duration of seismic waves[9]. Therefore,
when performing dynamic analysis on the structure of metro stations, it is necessary to select appropriate
ground motion parameters. The analysis results can more accurately predict the response and safety of
the structure, when it is subjected to earthquakes.

Time-course analysis is the principle of seismic wave selection[10]: the input seismic wave should
be consistent with the design response spectrum in statistical sense. The basis for selecting seismic wave
is: ① the category of the site; ② the characteristic period value of the ground motion acceleration
response spectrum; ③ structural vibration period; ④ reaction spectrum area size.

4. Selection of dynamic interaction parameters of soil-underground structure
The nonlinear problems of soil-structure interaction mainly include material nonlinearity, geometric
nonlinearity and boundary nonlinearity. Choosing a reasonable material constitutive model, model
elements and boundary conditions simplification processing according to the actual situation will be
directly related to the efficiency and accuracy of the analysis[11].
4.1. Elastoplastic constitutive model of the structure
Since the reinforced concrete structure is subjected to external loads, the internal forces and deformations of the structure will change nonlinearly with the nonlinear relationship between the section stress and strain. When studying the nonlinear relationship of structural materials, the constitutive relation of the model is often adopted. The internal force-deformation of the component can be corrected by adjusting the constitutive parameters of the model when the load is changed[12].

4.2. Elastoplastic constitutive model of soil
In the analysis of the performance of the soil in the project[13], the elastoplastic model is usually used to describe the influence of the stress path and stress history on the deformation during the analysis.

4.3. Ground-based infinite domain simulation
Liu Jingbo et al[14] proposed a viscoelastic artificial boundary method based on the viscous boundary. The boundary condition of the semi-infinite domain is approximated as a continuously published viscoelastic boundary. Radiation damping of the semi-infinite foundation is better simulated while simulating the elastic recovery performance of the boundary, which improves accuracy, making the calculation process more stable.

5. Finite element dynamic analysis

5.1. Unit selection
Using MIDAS software for modeling calculations, as shown in Figure 1 and Figure 2, considering the complexity of the structure and surrounding geological conditions, the calculation model is simplified accordingly:

(1) For the structure of the metro station, we can ignore the influence of the smaller opening, and adopt the average layer height modelling.

(2) The soil conditions around the metro station are complex, taking the parameters of typical soil layers, assuming that the soil properties of other soil layers are the same.

(3) The station pile foundation is calculated together with the soil body, and is equivalent to an orthotropic anisotropic material.

(4) Assuming that the main structure of the station and the surrounding soil are in close contact, and no relative displacement will occur.

(5) The vertical seismic action is not considered in the study, and only the structural dynamic response under horizontal earthquakes is studied.

(6) The traveling wave effect is neglected in the study, assuming that the seismic action comes from the bedrock surface and the motion of each point is the same.

5.2. Boundary processing
The boundary conditions adopt the concentrated viscoelastic artificial boundaries. The spring-damper parameters at different positions are calculated according to the geological data of the soil layer. The spring constant K1 and damping coefficient C1, which along the normal direction of the artificial boundary. The spring constant K2 and damping coefficient C2, which along the tangential direction of the artificial boundary. The formula is:

\[ \begin{align*}
K_1 &= \frac{4G}{R}A \\
C_1 &= \rho c_p A \\
K_2 &= \frac{2G}{R}A \\
C_2 &= \rho c_s A
\end{align*} \] (2)
R is the distance from the scattering wave source to the boundary node, which is taken as the shortest distance from the center of the calculation region to the corresponding boundary surface; A is the dominant area of the node; and $c_p$ is the dielectric elastic longitudinal wave velocity and $c_s$ is the transverse wave velocity, which are respectively calculated as:

$$c_p = \sqrt{\frac{1-\mu}{\rho(1+\mu)-(1-2\mu)}}$$
$$c_s = \sqrt{\frac{E}{2\rho(1+\mu)}}$$

(3)

5.3. Damping definition
In the interaction system, the damping characteristics are determined by the properties of the soil, because in the soil-structure interaction system, the damping properties of the soil material are greater than the damping of the structural material. It is known from the theory of soil dynamics that the response frequency of the soil has little effect on its damping characteristics. Therefore, the material damping defined in the calculation has nothing to do with the response frequency.

6. Calculation results and analysis

6.1. Structural acceleration response results and analysis
Entering the seismic wave (EL-centro, Taft wave, artificial wave) with exceeding probability of 10% and 50 year return period, the acceleration response envelope is shown in the figure:

![Figure 3. Acceleration envelope](image1)

![Figure 4. Acceleration history](image2)

It can be seen from the figure that under the action of Taft wave, the acceleration of the top layer and the first floor of the structure is the largest, the EL-Centro wave is the second, and the artificial wave is the last. The acceleration response under the artificial wave at the bottom plate is greater than that of the EL-Centro wave. The biggest one is still Taft wave; no matter under which seismic wave, from the bottom plate to the top plate, the acceleration response gradually becomes larger, and changes regularly along the floor, but the magnitude of the change is different. The top plate of the structure is n times the acceleration response of the bottom plate, and the value of n is 2.8 under the action of Taft wave, 2.2 under the action of EL-Centro wave, and 2.0 under the action of artificial wave.

Figure 4 below shows the maximum acceleration response time history curve at the top plate under the action of three seismic waves.

It can be seen from the figure that the waveform of the structural acceleration response is similar to the waveform of the input ground motion, and the peak of the reaction occurs at a position close to the peak of the input ground motion.

6.2. Structural horizontal displacement reaction results and analysis
Entering the horizontal seismic wave (EL-centro, Taft wave, artificial wave) with exceeding probability of 63% and 50 year return period, the acceleration response envelope is shown in the figure:

It can be seen from the figure that due to the different spectrum of seismic waves, even if their peak acceleration is the same, the horizontal displacement response caused by this is also very different. EL-
Centro wave and Taft wave are obviously higher than those under artificial wave. The trend of the reaction under the action of three kinds of seismic waves is the same, and it gradually increases upward from the bottom plate, and the maximum is the position of the top plate.

Figure 5. Displacement envelope

Figure 6. Displacement history

Figure 6 shows the maximum acceleration response time history curve at the top plate under the action of three seismic waves.

It can be seen from the figure that the waveform of the structural acceleration response is similar to the waveform of the input ground motion, and the peak of the reaction also occurs at a position close to the peak of the input ground motion.

6.3. Structural internal force reaction results and analysis

Figure 7 is the bending moment diagram of the cylinder of the metro station when the EL-Centro wave is applied at exceeding probability of 3% and 50 year return period (PGA = 310 gal). It can be seen that for the upper column, the bending moment of the top of the column is large. In the lower column, the bending moment at the bottom of the column is larger, and the bending moment of the column at the two ends of the station is larger than the bending moment of the central column. The seismic wave in the horizontal direction with exceeding probability of 63% and 50 year return period, and the top and bottom bending moment distributions of the structural columns calculated by different seismic waves are consistent with the following figure.

Figure 7. Column bending moment diagram

Figure 8. Displacement contour line

Figure 8 shows the horizontal displacement contour and column displacement contour of the overall structure of the soil-metro station obtained under the action of horizontal and vertical two-way coupled big earthquakes. It can be seen from the figure: the displacement of the reinforced concrete in metro station under the action of the earthquake increases along the floor, and the deformation reaches largest at the position of the free surface.

7. Summary

This paper analyzes the horizontal seismic response of the Qinghe station structure in Nanning Metro by using MIDAS software.

(1) The displacement of the central column of the metro station under the action of earthquake increases continuously along the location, because the seismic wave amplification factor at the free
surface of the soil is large under the action of earthquake, the deformation of displacement the soil is large. The underground building is restrained by the surrounding soil, under the influence of the large deformation of the surrounding soil, the closer the underground building is to the free surface of the soil, the greater the deformation of displacement will be, and of course, it will be easier to be destroyed, it is concluded that the inertial force is not the main cause of the damage of the underground building structure. The destruction of the underground building under the action of the earthquake is caused by the displacement difference caused by the deformation of the soil around the structure and plays a controlling role.

(2)Because the metro station building slab and the two side walls are connected by rigid joints, the side walls on both sides of the station structure serve as the main lateral force components for the underground building to resist the horizontal earthquake. The side walls and the roof, the basement and the second floor underground, the stress of whose connection position varies greatly.

(3) Under the action of different seismic waves, the variation of structural acceleration response and horizontal displacement response gradually increases from the bottom plate to the top plate, reaching the maximum value in the top plate; the acceleration coefficient of the structural roof plate is larger, and the amplification effect is stronger, which means The roof structure is subjected to the most exciting force and is easily damaged. Due to the constraints of the surrounding soil, the interlayer displacement response of each layer of the structure is small, and the displacement angle between the layers is smaller than the specified value of the displacement angle (1/550), indicating that the underground structure has better seismic performance.

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