Effect analysis of central column on seismic dynamic response of metro station structure

Youyi Lv, Ye Cao
China National gold group co. LTD, Beijing 100011

Corresponding author’s e-mail: 44013482@qq.com

Abstract. When the metro station structure has central column or no central column, the metro station structure shows different patterns of destruction. In this article, based on the nonlinear elastic-plastic finite element model for metro station, considering the structure-soil dynamic interaction, the influence laws of the central column on the dynamic response and failure mode of the metro station structure under near and far-field earthquakes are studied. We found that the horizontal displacements and dynamic amplification factors of the metro station with central columns is less than those of the metro station without central columns under near and far field earthquakes, and the existence of central column effectively inhibits the deformation and vibration of the metro station under earthquake, and improves the stability of the metro station.

1. Introduction

Metro stations are located on urban trunk roads or in urban residential areas, business districts or the most populous areas in general. In case of a devastating disaster, it may generate a chain and scale effect, leading to aggravated hazards and a series of very serious infrastructure damages, such as cracking of neighboring buildings and rupture of underground pipelines. In recent years, seismic actions have triggered damage of a great many underground structures [1][2]. For example, the Great Kanto Earthquake in Japan in 1923 (M8.2) destroyed 82 tunnels in the earthquake region; the Kern Earthquake in California in 1952 (M7.6) seriously damaged four tunnels of the Southern Pacific Railroad; the Izu Earthquake in Japan in 1978 (M7.0) resulted in fractures across tunnels and a series of damage of the tunnel lining; particularly, the Great Hanshin Earthquake in Japan in 1995 (M7.2) ruined some underground metro stations and section tunnels in Kobe. In Dakai Station, more than a half of the central columns were completely collapsed, resulting in roof collapse and enormous sedimentation of the overlying soil. The massive earthquake damage of underground structures have gradually aroused people’s attention to its seismic safety [3]. The issue of earthquake resistance of underground structures is attracting more attention of seismologists in all countries of the world.

The dynamic characteristics of underground structure are controlled by the surrounding foundation soil. Meanwhile, foundation soil is also influenced by underground structure, so it is necessary to take account of the interaction between soil and structure [4]. Hashasha [5] pointed out that when underground structure shakes at a low level under low-intensity seismic action or is in hard rock or other media, the results calculated by quasi-static method are acceptable. Otherwise, the influence of structure-soil interaction on underground structure should not be neglected. G.Gazetas [6] studied the influence of structure-soil interaction on the dynamic response of underground structure under seismic action, and concluded that the influence of structure-soil interaction on underground structure cannot be neglected. Youssef M.A. Hashasha [7] stated that when underground structure shakes at a low level under low-intensity seismic action or is in hard rock or other media, the results calculated by quasi-static method
are acceptable. Otherwise, the influence of structure-soil interaction on underground structure should not be neglected. Furthermore, the seismic resistance of underground structure is also affected by central column, making the anti-seismic research of the underground structure more complex [8][9].

In this study, this article established a nonlinear elastic-plastic finite element model for metro station structure based on soil-structure interaction, and we studied the influence laws of central column on seismic dynamic response of metro station under near and far-field earthquakes. Thus, we expected to provide reference and guidance value for engineering practice by obtaining some basic laws of metro station under seismic action.

2. Calculation Model

2.1. Establishment of a Numerical Simulation Model

The simpler a numerical simulation analysis model is, the more likely it reflects the universality of the laws. Therefore, this article generalized and modeled metro stations. A rectangular metro structure was selected as a research object. The metro station structure is 22m wide, 15m high and 1m thick, the calculation area of the structural part is 22m×15m, and the burial depth of the station is 20m. The artificial boundary of the calculation site is twice of the width of the metro structure. The distance of the artificial boundary from a bottom side to a bottom side of the metro station is 25m, in other words, the width is 110m and the depth (including structure) is 60m. The metro structure was treated as single-phase medium. The soil constitutive model adopted Mohr-Coulomb, the station structure adopted a linear elastic constitutive model, and meanwhile Rayleigh damping was selected to simulate damping effect [10-12]. Soil and metro station structure both adopted rectangular grid 1m×1m adopted by the plane strain unit to conduct discrete operation. The left boundary, right boundary and bottom boundary of the model all adopted free field boundaries. In the calculation process, no disengagement and slump between soil and structure were considered, and only complete cohesion between them was considered. The geometric model and numerical simulation model for metro station are as shown in Figure 1. Physical parameters of site soil and station structure are as shown in Table 1.

![Figure 1 Numerical model and monitoring numbers of metro station](image)

| Name    | Density (kg/m³) | Modulus of Shear | Poisson’s | Cohesion | Internal | Yield |
|---------|-----------------|------------------|-----------|----------|----------|-------|
|         |                 |                  |           |          |          |       |

Table 1 Physical and mechanics parameters
3. Influence of Soil Properties

The soil properties are crucial for the dynamic response of the metro station. The soil data is provided in the table below:

| Soil Type       | Elasticity Modulus (GPa) | Modulus Ratio (GPa) | Friction Angle (°) | Strength (N/mm^2) |
|-----------------|--------------------------|---------------------|--------------------|-------------------|
| Site Soil       | 2100                     | 0.54                | 0.36               | 27                | \                |
| Interlayer      | 2650                     | 0.01                | 0.004              | 10                | 15               |
| Metro Station   | 2500                     | 17.3                | 11.5               | \                | \                |

2.2. Selection of Seismic Waves

The site for the metro station is set as type II. When numerical simulation methods are adopted for dynamic response analysis of earthquakes on structures, the measured boundary seismic waves (Type I: T1-II-1 seismic waves, high occurrence frequency, large amplitude and long action) and inland epicentral seismic waves (Type II: T2-II-1 seismic waves, short time strong earthquake) are calculated as far-field earthquake records and near-field earthquake records respectively, as shown in Table 2. Seismic fortification intensity is scale VIII, and design basic seismic acceleration value is 0.2g, as shown in Figure 2.

| Type No          | Name of Earthquake             | Magnitude | Distance to Epicenter/km | Place of Record | Acceleration Peak/Gal |
|------------------|--------------------------------|-----------|--------------------------|-----------------|-----------------------|
| T1-II-1          | Hyūga-nada Earthquake in 1968 | 7.5       | 100                      | Bandao Bridge Foundation | 318.84                |
| T2-II-1          | Kobe Earthquake in 1995        | 7.2       | 11                       | JR Yingqi Station | 686.83                |

Figure 2 Time history of seismic wave

3. Influence law of central column on the dynamic response of the metro station

We studied the dynamic response of the metro station with central column and no central column, as shown in Figure 3 and Figure 4.

Figure 3 The maximum horizontal displacement of the roof under near and far field earthquakes
As shown in Figure 3 and Figure 4, under T1-II-1 and T2-II-1 earthquakes, the horizontal deformations on the roof and side walls of the metro station structure show a same change law, and the horizontal displacement of the roof and side walls of the metro station with central columns is less than the horizontal displacement of the metro station without central column, which shows that the deformation of the roof and side wall of the metro station with central columns is effectively inhibited. The existence of central column effectively inhibits the deformation of the metro station under seismic action, and improves the deformation stability of the metro station.

As shown in Figure 5 and Figure 6, under T1-II-1 and T2-II-1 earthquakes, the horizontal dynamic amplification factors of the roof and side wall of the metro station structure show a same change law.
When there are central columns, the horizontal amplification factors of the roof and side wall are less than those of the metro station without central columns as a whole, which shows that the vibration on the roof and side wall of the metro station with central columns is effectively inhibited. Central column have a good damping effect on the metro station and properly stabilize the vibration of the metro station under near and far field earthquakes.

4. Conclusions
The horizontal displacements and dynamic amplification factors of the roof and side walls of the metro station with central columns is less than those of the metro station without central column under near and far field earthquakes, which shows that the deformation and vibration of the roof and side walls of the metro station with central columns are effectively inhibited. Thus, the existence of central column effectively inhibits the deformation and vibration of the metro station under earthquake, and improves the stability of the metro station.

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