Seismic response analysis of subway underground stations using split columns

Shao Wen
China Railway First Survey and Design Institute Group Co., Ltd. Xi’an, ShaanXi. 710043

Abstract. Taking the underground station research project of the first phase of Nanning Rail Transit Line 4 as the engineering background, based on the ABAQUS large-scale finite element software, the numerical integration method, the constitutive relationship of structural materials and the determination of boundary conditions appear in the model establishment. The key problems of seismic wave selection and input are analyzed. The appropriate 3D standard section metro station structure calculation model is established. The seismic wave baseline drift phenomenon occurs in the dynamic time history analysis of ABAQUS. The Seismic Signal software is used to correct the seismic wave baseline. On the basis of theoretical analysis, through the numerical simulation, the dynamic time-history analysis of the frame column and the split column in the metro station under the two-way coupled seismic action is carried out, and the elastoplasticity of the metro station adopting the frame column and the split column is carried out. Time-history analysis found that the bearing capacity of the split column under the large earthquake is about 16% lower than that of the frame column, but the ductility is increased by about 35%. In other words, the split column loses part of the bearing capacity and changes the force of the frame column. Features greatly improve the ductility of the column.

1. Introduction
With the rapid development of China's economy, a large number of people gather in cities, and the problem of urban traffic congestion is becoming more and more serious. Some central cities can develop and utilize less space resources on the ground, and the ground building structure can no longer meet the traffic and commercial demand, in order to alleviate traffic pressure, solve urban traffic congestion and the resulting environmental pollution, more and more cities have begun to develop large-scale and use underground space, and the subway has gradually become a solution to urban traffic congestion [1].

The destruction of underground structures in earthquakes is different from that of above-ground buildings. Once a subway station and a section tunnel are destroyed, it will not only affect the lifeline engineering of urban buildings (underground water supply and drainage pipes, natural gas pipelines, etc.), but also the emergency things after the earthquake and the repair work after the earthquake brought great difficulties [2]. The structure of the metro station is buried deep in the soil, and the existence of the surrounding geotechnical medium has a binding effect. At the same time, the interaction between the surrounding geotechnical medium and the structure makes the seismic response of the underground structure different from the above-ground structure. The seismic analysis of underground structures and above-ground buildings is affected by the vibration characteristics of the structure and the vibration characteristics of the foundation soil, but the seismic response of the upper building mainly depends on the structural self-vibration characteristics, including the shape and stiffness of the upper building. Quality, etc.; for underground station structures, the characteristics of
the surrounding geotechnical media will have a decisive impact on the building’s response to the earthquake. At this time, the seismic design method of the above-ground buildings will no longer be applicable to the underground structure, and the interaction of the soil-underground buildings will easily change the response characteristics of the land around the site, which in turn will affect the earthquakes of the building structures that have been built and under construction. This paper takes the underground station of the first phase of Nanning Rail Transit Line 4 as the background. Based on the ABAQUS large-scale finite element software, the appropriate finite element analysis model is established by using the fiber unit to project the subway station structure with frame column and split column respectively.

2. Overview of the structure model of soil-metro station
The station is a two-story underground platform on the island platform station. The total length of the station (outsourcing length) is 207.6m and the standard section is 19.7 meters wide. In order to facilitate the computational analysis of the finite element software ABAQUS, the numerical simulation calculation time is greatly reduced, and the main structure of the metro station is simplified when the finite element model is established. Since the spacing between adjacent columns of the standard segment structure is 9 m, the model is in the longitudinal direction. The direction is 9m and the calculation model of the concrete metro station structure is 19.7m×15.53m×9m. The main structural dimensions of the station are shown in Table 1 below. The sectional view of the standard section of the station structure is shown in Figure 1. According to the initial survey data given by the Geological Survey Engineering Institute, the main data of the soil around the building structure of Qingping Station are shown in Table 2.

| Station structure   | Size (mm)         |
|---------------------|-------------------|
| roof                | 800               |
| Medium plate        | 400               |
| Bottom plate        | 900               |
| Top beam            | 1200×1800         |
| Middle beam         | 1000×1000         |
| Bottom beam         | 1200×2200         |
| Side wall           | 700               |
| Frame column        | 700×1200          |
| Split column        | 700×1200          |
Figure 1 Station structure section

Table 2 Site land quality data and parameters

| Layering | Geology name          | density | Water content | Shear experiment | Bearing capacity of foundation |
|----------|-----------------------|---------|---------------|------------------|--------------------------------|
| 1        | Miscellaneous fill    | 1.90    | /             | 10.0             | 6.0                           | 70                             |
| 2        | Prime fill            | 1.96    | /             | 13.0             | 10.0                          | 80                             |
| 3        | Silty clay            | 1.91    | 28.8          | 46.0             | 12.0                          | 180                            |
| 4        | Weathered limestone   | 1.65    | /             | 800.0            | 55.0                          | 1800                           |

3. Model establishment

In this paper, the beam and column are selected based on the fiber rod element model of the material. The uniaxial constitutive relationship of the concrete material is shown in Fig. 2. The reverse reloading rule of the steel bar is shown in Fig. 3. The PQ-Fiber applet is used [3], PQ- Fiber is a collection of uniaxial hysteretic constitutive models of a set of materials developed by the Institute of Structural Engineering of the Department of Civil Engineering of Tsinghua University based on the large general finite element program ABAQUS.

Figure 2. Concrete uniaxial constitutive

Figure 3. Rebar reverse reloading rules
In the analysis of wallboard members, layered shell elements are used. The layered shell elements can relate the material constitutive relationship of concrete and steel bars to the nonlinearity of plane buildings such as shear walls and floors, and simulate planes such as shear walls and floors. Building complex nonlinear behavior has great advantages. The concrete constitutive adopted by the shell element is the CDP (Concrete Damaged Plasticity) constitutive of the ABAQUS finite element software. The concrete plastic damage model (CDP model) used needs to predefine five material parameters in the attribute module. When defining, considering the convergence, rationality and analysis efficiency of the numerical model calculation results, it is recommended to use the numerical values as shown in Table 3.

| Model parameter | Expansion angle | Offset value | Initial yield strength ratio | \( K_v \) | Viscosity coefficient |
|-----------------|-----------------|--------------|-----------------------------|--------|---------------------|
| Value           | 30              | 0.1          | 1.16                        | 0.6667 | 0.0005              |

The soil around the station structure adopts three-dimensional solid elements. According to the geological survey data of each layer of soil, the nonlinear behavior of the material in the elastoplastic time-history analysis shows different reaction results in various parts of the soil. When the numerical model simulates the influence of the soil around the station structure on the main building of the station, the following two points are mainly considered: the soil constitutive model in the infinity area is the elastic model, and the constitutive model of the near-field limited area soil is Mohr. The Coulomb plasticity model requires attention when using the Mohr-Coulomb criterion: (1) The Mohr-Coulomb strength criterion uses non-associative flow criteria, so an asymmetric solver is used, which is the Mohr-Coulomb model. A very important one in use, if it does not cause enough attention, it is easy to appear that the model is interrupted due to non-convergence. The setting of the asymmetric solver is in the other dialog box in the Edit step dialog box of ABAQUS. (2) The value of cohesion in the Mohr-Coulomb strength criterion must be greater than zero.

Research and analysis show that there are usually some long-period components in the acceleration record, although they will not cause the drift of the acceleration time history, but it will cause severe drift to the displacement time history after integration [4]. In this paper, the SeismoSignal seismic wave processing software is used to process the selected seismic waves, and the typical US EL-centro wave seismic data is selected for calculation. In order to save the calculation time, only the time history of the representative acceleration peak in the seismic displacement time history is selected for 20s. The curve is analyzed, and the time step is taken as 0.02 s for analysis and calculation, and is input at the bottom boundary in the form of bedrock waves.

In the dynamic time history analysis, the peak value of the seismic record should be adjusted according to the requirements of different seismic fortification intensity. The specific amplitude modulation coefficient is based on the acceleration of the dynamic time history analysis of the different intensity intensity defense area according to the Code for Seismic Design of Buildings [5]. The peak value is adjusted, so the ground motion amplitude modulation is adjusted to small earthquakes (35 gal) and large earthquakes (220 gal) to consider the seismic performance of different medium-column columns in the structure of subway stations under small earthquakes and large earthquakes.

In the dynamic analysis of underground structures, in dynamic analysis involving infinite bounds, it must be considered that the natural foundation is infinitely extended, the ground energy will escape to infinity [6], and the finite element mesh simulation is used to establish the model. The near-field region of interest uses infinite elements to simulate far-field regions away from the structure. In this paper, the numerical model uses CIN3D8 three-dimensional infinite element to simulate the soil in the far field of the underground building. Considering the radiation effect of the wave at the artificial boundary, when using the infinite element as the transmission boundary, the model pre-processing should be Note the points, as shown in Figure 4:

1. The number of nodes in the infinite element is to ensure that the first face of the element is the intersection of the finite element and the infinite element. This ensures that the seismic wave is from
the main structure of the underground building and the near-field body when the seismic wave reaches the artificial boundary. When it is transmitted, the seismic wave will not refract the wave at the artificial boundary.

2. The infinite element unit does not allow intersection in its outward extension.

3. The order of the node numbers in the infinite element unit must match the order in the entity unit.

4. ABAQUS can not directly define an infinite element. You can first assign other unit attributes to the unit to be set to infinite, and define the infinite element by modifying the unit type and node number.

This model uses \( lm \times lm \) square elements to mesh the surrounding soil, and meshes the reinforced concrete structure of the metro station with a square unit of \( 0.2m \times 0.2m \). When the model is established, consider several assumptions: (1) Each layer of soil around the station structure is composed of layers of soil that are independent of each other and extend infinitely in the horizontal direction; (2) the properties of each layer of soil are the same, but can vary with the position of the soil layer. The lowest layer of soil is covered on the rigid bedrock surface, that is, each layer of soil is homogeneous and isotropic; (3) It is assumed that there is no detachment and relative sliding between the soil-metro station structures, that is, the displacement deformation coordination is satisfied. (4) It is assumed that the seismic wave is a shear wave and a compression wave that propagate vertically upward from the bedrock surface, and does not consider the oblique incidence of the seismic wave; (5) Under the action of the seismic wave, the pore water pressure and the liquefaction of the sand are not considered.

The simulation of the interaction between the main structure of the underground station and the surrounding soil, through the establishment of contact pairs on the surface of the component, using the algorithm of the master-slave contact surface in the ABAQUS software, and assuming that under the action of seismic waves, the main structure of the station and the surrounding soil are not Sliding and disengaging are generated, that is, the displacement deformation coordination condition is satisfied, as shown in Fig 4. The three-dimensional finite element model of the foundation soil-station structure is shown in Fig. 5.

![Figure 4. master-slave constraint](image1)

![Figure 5. Three-dimensional finite element model](image2)

4. Numerical simulation results analysis

The dynamic elastoplastic time history analysis of the metro station with frame column and split column is carried out, and the time history curve of seismic wave displacement obtained by adjusting the “baseline correction” is input. The reinforcement of the fiber unit frame column and the core column is shown in Fig. 6.

![Figure 6. Fiber unit frame column and split column reinforcement](image3)
4.1 Structural acceleration response results and analysis
The acceleration response values of each floor of the main structure of the metro station analyzed by the metro station structure using frame columns and split columns are considered as shown in Figure 7 below.

![Figure 7. Acceleration response along the floor](image)

Table 4 shows the structure of the station structure using the frame column and the split column in the roof, considering the horizontal and vertical two-way seismic small earthquakes (PGA=35gal) and large earthquakes (PGA=220gal). The horizontal acceleration response value at the basement and underground two-story beam-column joints.

| name         | Frame column | Split column |
|--------------|--------------|--------------|
|              | Small earthquake | Shock | Small earthquake | Shock |
| roof layer   | 86.5         | 336.3        | 80.8           | 326.3 |
| second floor | 77.8         | 309.6        | 74.3           | 306.8 |
|              | 58.3         | 270.1        | 56.7           | 267.2 |

It can be concluded from Table 4 that the metro station structure using the frame column and the split column shows that the maximum acceleration of each floor is gradually increased from the second floor of the underground, and the acceleration response at the position of the roof is the largest, considering the effect of the large earthquake. Next, the acceleration factor of the underground layer of the metro station using the frame column is 1.245, and the acceleration factor of the underground layer of the metro station using the split column is 1.22. Under the action of earthquakes, the earthquakes at the location of the underground layer are more affected, and the earthquake response is obvious.

4.2 Structural horizontal displacement reaction results and analysis
The horizontal displacement of each floor of the main structure of the metro station, which is analyzed by the horizontal and vertical two-way seismic large earthquakes (PGA=220gal), is shown in Fig. 8 for the metro station structure using frame columns and split columns.

Tables 5 and 6 respectively show the structure of the station that is analyzed by the frame column and the split column in consideration of horizontal and vertical two-way seismic small earthquakes (PGA=35gal) and large earthquakes (PGA=220gal) and the displacement between layers and the displacement angle between layers in the roof, underground layer and underground two-story beam-column joints.
It can be seen from Table 5 and Table 6 that the maximum displacement of the beam-column joints in the top, underground and underground layers of the metro station is gradually reduced from the top of the structure. Considering the joint action of horizontal and vertical two-way earthquakes, the maximum displacement angles of the interlayers of the station using frame columns under multiple encounters and rare earthquakes are 1/5727 and 1/1340, respectively. The maximum displacement angles of the floors in the multiple encounters and rare earthquakes are 1/3500 and 1/733, respectively. This is because the underground buildings are constrained by the surrounding soil, and the subway stations use frame columns or split columns. The variation of interlayer displacement at each floor is very small, and the maximum displacement angle between layers in the case of multiple earthquakes and rare earthquakes is far lower than the interlayer displacement specified in the Code for Seismic Design of Buildings (GB50011-2010). The angular limit is 1/550 (multiple earthquakes) and 1/50 (rare earthquake), which indicates that the underground buildings do have a good ability to resist earthquakes. Under the action of large earthquakes, the maximum displacement of the split columns is used in subway stations. The maximum displacement of the frame column is increased by about 35%, which means that the separation column is used instead of the frame column to change the force characteristics of the original column, which greatly improves the ductility of the column.

4.3 Structural internal force reaction results and analysis

Table 7 and Table 8 respectively show the axial force of the metro station structure using frame columns and split columns in consideration of horizontal and vertical two-way seismic small earthquakes (PGA=35gal) and large earthquakes (PGA=220gal) and shear.
Table 8. Shear force of different columns

| name     | Frame column |       | Split column |       |
|----------|--------------|-------|--------------|-------|
|          | Small earthquake | Shock | Small earthquake | Shock |
| layer    | 54.93        | 302.11 | 48.81        | 249.13 |
| Second floor | 41.44        | 241.59 | 37.25        | 192.46 |

It can be concluded from the table that the change of the internal force of the central column of each floor has a certain relationship with the change of the displacement between the layers of each floor. If the displacement of the floor is large, the internal force of the column of the layer is larger. Under the action of large earthquakes, the axial force of the split column and the axial force of the frame column are less than 9%, and the shear force difference is about 16%. The central column of the metro station is the main force in the underground building. The components are also the most severely damaged components in the seismic response process. The central column of each floor of the station structure has suffered a lot of internal forces during the earthquake, and its stress process is more complicated. Therefore, when the seismic design of underground buildings is adequate, it should be given enough value.

5. Conclusion

The subway station adopts frame column and split column. The maximum interlayer displacement angle of each floor is far less than the interlayer displacement angle limit specified in the Code for Seismic Design of Buildings (GB50011-2010), and both show good seismic resistance. The bearing capacity of the split column and the axial force of the frame column are less than 9%, the shear force difference is about 16%, but the ductility of the split column is increased by about 35%. Under the condition that the bearing capacity meets the requirements, the split column is used to change the force characteristics of the frame column, and the ductility of the column is improved. The load of the frame column is changed by the sacrificial part bearing capacity, which greatly improves the ductility of the column. Therefore, in the actual project, the split column can be used instead of the traditional frame column, so that the ductility of the central column of the metro station can better adapt to the deformation of the soil around the building structure and improve the seismic performance of the underground station.

It is impossible to establish an underground building that can resist the earthquake movement and displacement deformation of the soil around the structure forever. Therefore, under the condition that the bearing capacity meets the design requirements, the underground building has sufficient deformation capacity to absorb the energy consumed, and the underground building can be made. The ductility of the building adapts to the deformation of the soil around the building structure, and not only the underground building can resist the displacement deformation of the surrounding soil, etc., which requires a change in the previous understanding of the seismic performance of underground buildings. Through the research and analysis of this paper, the subway underground station adopts the split column instead of the traditional frame column, which not only has better seismic performance, but also has a great improvement in ductility under the condition that the bearing capacity meets the requirements. The split column can be very good. Adapt to the displacement deformation of the soil medium around the underground building structure.

References

[1] Li Weichao. Optimum Design of Urban Rail Transit Metro Station Building Based on the Perspective of Large Passenger Flow[J]. Architectural Engineering Technology and Design, 2014(31).

[2] Cheng Duoduo. Seismic ductility analysis of urban underground structures and underground space safety management [D]. Southeast University, 2010.
[3] PQ-Fiber_Manual_v1.6.
[4] Wang Wei. Research on seismic analysis method based on FLAC and its application in underground tunnel[D]. Hohai University, 2008.
[5] Code for Seismic Design of Buildings (GB50011-2010)
[6] Li Li. Research on Seismic Dynamic Response of Expressway Tunnel Based on ABAQUS[D]. Southwest Jiaotong University, 2009.