Research on earthquake damage mechanism of a subway station structure based on centrifuge shaking table tests and numerical analysis

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Abstract: During the 1995 Kobe earthquake, the Daikai subway station witnessed serious collapse, which attracted the attention of people to the earthquake damage response of the subway structure. To study the earthquake failure mechanism of a subway station structure, two comparative dynamic centrifuge tests were performed. During the centrifuge tests, many important physical quantities cannot be directly monitored with appropriate instruments due to many limitations, such as extremely small model structures, extremely high collection frequency and complex centrifugal environment. To study the earthquake failure mechanism of a subway station structure in depth, an extended analysis of model tests was performed by means of numerical model. Finally, the earthquake failure mechanism was summarized in detail based on the numerical analysis.

1. Introduction
It is generally believed that the seismic performance of underground structures is better than that of above-ground structures, and it is not easy to be severely damaged under earthquakes[1]. However, the Daikai subway station completely collapsed in the 1995 Kobe earthquake[2]. This event shows that the underground structure also has the risk of collapse damage under the strong earthquake.

In view of the serious damage of the Daikai station, a large number of studies have been conducted on the earthquake damage mechanism of a subway station structure. As for the internal factors leading to the structural collapse, most researchers argued that the destruction of the Daikai station was due to the lack of seismic capacity of columns[2-13]. The lack of seismic capacity can be further divided into two aspects, including the inadequate bending-shear capacity[2,3,5,8,11-13] and poor horizontal deformation capacity[4,6,7,9,10] of the columns. At the same time, some scholars believed that the key reason for the failure of the Daikai station was the insufficient deformation capacity in the sidewalls and slabs[14,15]. Taking into account the external factors affecting the seismic response of underground structure, some scholars suggested that the horizontal earthquake is the key cause for the collapse damage at the Daikai station[2]. Meanwhile, some researchers argued that the joint action of horizontal and vertical earthquake caused the structural collapse [8]. Du et al. [9] and Ma et al. [10] hold an opinion that the vertical seismic action would significantly increase the axial pressure of the column, thereby reducing its horizontal deformation capacity. High axial compression columns were prone to brittle failure under the action of horizontal earthquakes, leading to structural collapse.
According to previous studies, so far, there is no consensus on the explanation of the earthquake damage mechanism of a subway station structure.

This paper means to shed light on the earthquake damage mechanism of a subway station structure through two comparative centrifuge shaking table tests. Because of the limitations of experimental technology in centrifuge tests, there are a lot of physical quantities could not be directly monitored, such as the axial force, shear force, and bending moment of components. So, an extended analysis of tests were performed by means of numerical model to perform an in-depth research on the earthquake failure mechanism of a subway station structure.

2. Experimental design
The model tests were carried out on the centrifuge shaking table of Zhejiang University. The shaking table facility cannot provide the vertical action, so the vertical earthquake motion of overlying soil cannot be directly simulated. According to prior numerical researches [9-10], the vertical earthquake plays an important role for seismic failure response of subway station structures. To surmount the limitation of the equipment, the steel sand was added into the overlying soil to approximately simulate the vertical earthquake action of overlying soil. Referring to the numerical results [9-10], the peak value of the vertical earthquake in overlying soil was about 0.4g ~ 0.6g. Therefore, 50% of the mass of the overlying soil is taken as the additional mass to approximately replace the vertical inertia of the overlying soil. Fig.1 displays schematic diagrams of test scheme of the soil-structure model systems. The similarity ratios of the model test are listed in Table 1.

![Fig.1 Schematic diagram of test scheme: (a) No vertical earthquake, (b) Considering vertical earthquake](image_url)

| Parameter         | Model | Prototype |
|-------------------|-------|-----------|
| Density           | 1     | 1         |
| Size/Displacement | 1     | 50        |
| Elastic modulus   | 1     | 1         |
| Bending stiffness | 1     | 50\(^2\)  |
| Compressive stiffness | 1    | 50\(^2\)  |
| Time              | 1     | 50        |
| Frequency         | 1     | 1/50      |
| Acceleration      | 1     | 1/50      |
| Stress            | 1     | 1         |
| Strain            | 1     | 1         |

The Fujian standard sand was used to make the model site, and its physical properties are tabulated in Table 2. The relative density of the site was controlled to 50% through artificial sand-rain device.

The steel wire with diameter of 7mm and low strength micro-concrete were used to make the model subway structure. The compressive yield strength of micro-concrete is about 20 MPa, and the elastic modulus is about 13 GPa. The dimensions and reinforcement of the model structure are shown in Fig.2.
A large number of sensors were used to record the seismic responses of soil-structure systems in the dynamic centrifuge tests, and the arrangement is shown in Fig. 3.

Table 2 Physical properties of model soil

| Parameter | $G_s$ | $e_{\max}$ | $e_{\min}$ | $e$ | $D_{50}(\text{mm})$ | $\phi$ / ° |
|-----------|-------|------------|------------|-----|---------------------|------------|
| Value     | 2.645 | 0.961      | 0.615      | 0.78| 0.16                | 39         |

Fig. 2 The size and reinforcement details of model structure

Fig. 3 Arrangement of sensors: (a) accelerometer, (b) strain gauges, (c) pressure cells

The peak accelerations of Kobe earthquake record were scaled to 0.1g, 0.32g, 0.4g, and 0.52g respectively, which were used as the input motion. The acceleration record and Fourier spectrum of input motions are shown in Fig. 4.

Fig. 4 Acceleration record and Fourier spectra (prototype scale)
3. Comparison of macroscopic phenomena in model structure

As shown in Fig.6, the SSI-1 model structure did not witnessed visible damage during the earthquake (0.1g~0.52g). The SSI-2 structure collapsed seriously during the 0.4g earthquake motion, and its failure development process is shown in Fig.5. Cracking damage occurred at the top of the column first(Fig.5 (b)), and then the failure area gradually developed from the top to the bottom of the component(Fig.5 (c)). Finally, the complete brittle failure occurred at the columns and the ceiling slab of the structure collapsed seriously(Fig.5 (d)). As shown in Fig.6, serious cracking witnessed near the intersection of the ceiling slab and sidewalls. According to the failure development process of SSI-2 structure, it can be concluded that the failure of columns is the main reason for the collapse of the model structure. By comparing the test conditions of SSI-1 and SSI-2 tests, it can be seen that the different inertia effect of the overlying soil is the important reason for the different damage modes of two tests.

![Fig. 5 Failure development process of SSI-2 model structure](image)

![Fig. 6 The macroscopic damage detail of the model structure](image)
4. Analysis of earthquake failure mechanism of a subway station structure based on numerical model

In the dynamic centrifuge tests, many important physical quantities cannot be directly monitored with appropriate instruments due to many limitations, such as extremely small model structures, extremely high collection frequency and complex centrifugal environment. The above shortcomings make it difficult to analyze the earthquake damage mechanism quantitatively only through the macroscopic damage phenomenon of the structure and the test data. Therefore, the numerical analysis was introduced to shed light on earthquake failure mechanism in the next section.

In order to improve the credibility of the numerical results, it was necessary to validate the numerical model via the dynamic centrifugal tests. The full dynamic time history analysis of soil-structure model was carried out using the finite-element program. A three-dimensional numerical model considering material nonlinearity and contact nonlinearity were established at prototype scale. The details of the numerical modeling is shown in Fig. 7.

The numerical results were compared with experimental records, including earthquake damage details and damage process of the model structure, horizontal acceleration response in model site, and structural dynamic strain. According to the comparisons[16], it was found that the numerical results were basically consistent with the test records, indicating that the numerical model could better simulate the dynamic response of soil—structure system.

![Fig. 7 Details of numerical modeling](image)

Based on the macroscopic failure response of the model structure, it could be concluded that the failure of columns is the main reason for the collapse of the model structure. A numerical model was established to simulate the relationship of horizontal shear force and deformation of a column under different axial pressures. The details of the numerical model are shown in Fig. 8. The horizontal deformations, shear forces and axial pressures were nondimensionalized, and are called as the relative displacement ratio, shear force ratio and axial pressure ratio, respectively. Fig.9 illustrated the relation curves of horizontal shear force ratio and relative displacement ratio under different axial pressure ratio. The relative displacement ratio corresponding to the peak shear force ratio was used to evaluate the horizontal deformation capacity of a column. These horizontal deformation ratios points were plotted with axial compression to obtain the deformation capacity envelope of a column, as shown in Fig. 10. The deformation capacity envelope showed that the horizontal deformation capacity of columns decreases with the increase of axial pressure.
The earthquake responses of the columns in SSI-1 and SSI-2 model structure are plotted with the corresponding deformation capacity envelope and presented in Fig. 11. Without consideration of vertical earthquake action, the axial compression ratio of the column of SSI-1 model is relatively small. Under the 0.52g earthquake, the horizontal relative displacement ratio of the column just touches the deformation capacity envelope. Compared with SSI-1, the column of SSI-2 is always at a higher axial pressure level. Under the 0.4g earthquake, the horizontal relative displacement ratio of the column far exceeds the deformation capacity envelope. The above analysis perfectly explains the difference in macroscopic failure phenomena of model structure between the two tests. Specifically, the column in the SSI-2 model structure under high axial compression witnessed less horizontal deformation capacity, which resulted in severe failure under relatively small horizontal earthquake.
Fig. 11 Earthquake responses of the column and deformation capacity envelope

5. Summary

Based on the above analysis results, the earthquake failure mechanism of subway station structures would be summarized as follows.

The vertical earthquake motion can obviously increase the axial pressure of the central column, which will significantly reduce the horizontal deformation capacity of columns. The high-axial compression column suffered a sudden brittle failure under the action of a strong horizontal earthquake, and lost the vertical support ability, resulting in the collapse of the ceiling slab. Therefore, the failure of columns is the main reason for the collapse of the model structure. So the columns are the important seismic components in a subway station structure. Based on the above analysis, if the column can avoid damage and always provide sufficient vertical support for the ceiling slab under the strong earthquake, the overall collapse risk of the subway station structure can be reduced.

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