Failure mechanism of subway structure with different central columns based on Daikai Station

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Abstract: The central columns of the Daikai Station in Kobe City were severely damaged due to Hanshin earthquake in the year 1995, leading to serious ground collapse. To evaluate the behavior of underground structures, the finite element model of Daikai Station was established using ABAQUS, and benchmarked against the measured data. Furthermore, the central column was replaced by concrete-filled steel tube (CFST) column to illustrate the response under the earthquake action. Results show that the central column of the station is one weak part of structure. Compared with the ordinary reinforced concrete (RC) structures, using CFST central column can enhance the overall rigidity of the structure and greatly improve the seismic performance of the underground structures.

1. Introduction

With the rapid development of urban subway transportation all over the world, the research on the seismic performance of underground structures has become a research interest in disaster prevention and mitigation [1, 2]. In the year 1995, the Daikai Station built between 1962 and 1964 was destroyed due to the Great Hanshin earthquake in Japan. Nearly half of the central columns completely collapsed, causing the maximum settlement of the overlying soil layer of 2.5 m, and the structure was destroyed as "M" shape [1].

Since the Hanshin earthquake, scholars have begun to use theoretical analysis, numerical simulation and model tests to explore the seismic performance of underground structures. Huo et al. (2005) [1] simulated the earthquake damage of Daikai Station using FE method, mainly focusing on the displacement time history curve of the central columns and the continuous change of axial shear force during the earthquake. Based on the three-dimensional non-linear numerical analysis model of the Daikai subway station (Du et al.2017) [3], the seismic destruction mechanism and mode of the station was systematically explained from the two seismic effects of the surrounding rock and soil on the shallow underground structure and the mechanical properties of the key components.

Recently, scholars have gradually carried out research on steel-concrete composite structure subway stations [4, 5]. However, most scholars currently primarily study the construction process simulation of the subway station using steel-concrete composite structures, the strength of the joints, and the overall basic mechanical properties. However, there are few studies on the seismic performance analysis of the steel-concrete subway station. This paper firstly carried out a numerical simulation analysis of the seismic damage response of the station in the Hanshin earthquake, and compared the FE results with the seismic damage phenomenon of the Daikai Station. Under the condition that the other parameters of the Daikai Station remaining unchanged, central column was replaced by CFST column, and their behavior
was further evaluated.

2. Establishment and verification of Daikai Station FE model

2.1. Introduction of Daikai Station
Daikai Station is constructed by open-cut method, both sides of the station are double-track concrete tunnels, and there are no obvious liquefied soil layers and fault areas around the station. Since the seismic design was not considered during the construction, the 31 central columns in the Daikai Station 15km away from the epicenter of the earthquake suffered shear failure. The destruction of the central columns directly led to the collapse of the roof, leading to the overlying soil to collapse with a maximum of 2.5m, with a collapsed area of about 2000m². It can be seen that the degree of damage to the underground structure caused by the Hanshin earthquake is unprecedented [6].

2.2. Establishment of FE model
The Daikai Station is 120m in length and consists of three parts, and this paper selected only the main part that was most damaged in the Hanshin earthquake. The cross section of the structure is 17m wide and 7.17m high; the wall thickness is 0.85m, and the reinforcement ratio is 0.8%; the thickness of the top and bottom slabs are 0.80m and 0.85m; and the reinforcement ratio is 1.0%. It also had a series of central columns with reinforced-concrete cross section 0.4 m by 1.0m with axial spacing of 2.5 m, and the clear height is 3.82m. The density of the steel bar is 7800kg/m³, the elastic modulus is 200GPa, and the Poisson's ratio is 0.1 [3].

A two-dimensional soil-structure model with a length of 1000m and a height of 58m was established using the ABAQUS software. Among them, the station is simulated by beam element B21, the unit weight, the elastic modulus and Poisson’s ratio of the concrete are set as 25 kN/m³, 24 GPa and 0.2, respectively; the steel bar is embedded in the column, and the relative slip between the bars and the concrete is neglected in the calculation process.

To better reduce the influence of the lateral boundary on the seismic wave reflection, this simulation uses the infinite element to simulate the wave scattering on the lateral boundary [7]. The boundary conditions of the model are as follows: the horizontal and vertical displacements are fixed at the bottom surface while the top of the structure is free; infinite elements were applied at the lateral boundaries and the ground motions are imposed at the bottom of the model. In addition, 4-nodes plane strain element (CPE4R) and the quadrilateral plane strain infinite element (CINPE4) are adopted for soil simulation.

![Infinite element](image1)

(a) Numerical model of Daikai Station and the surrounding soil

(b) Daikai Station FE model

Figure 1. FE model of Daikai Station.

2.3. Verification of FE model
The FE model was benchmarked against the results in Huo et al. [1] and Gustavo et al. [2]. The main content of the comparison is the horizontal displacement of the central column and the time history curve of the internal force. By extracting the acceleration time history curve at the bottom of the FE model and comparing it with the original input seismic wave, it can be seen that the seismic wave load of the FE model is similar to real seismic load.

By extracting the displacement time history curve of the central column of the Daikai Station, it can
be seen from Figure 2 that under the horizontal-vertical coupled ground motion, the maximum
displacement of the central column of the station is 3.275 cm, while the calculation result is 3.80 cm by
Huo et al. [1], the relative error is 13.82%.

![Figure 2. Central column distortion.](image)

It can be seen from Table 1 that before the earthquake occurred, the static axial force of the central
column of the station was 3354.64 kN; and during the earthquake the maximum axial force was about
5135.29 kN. The static axial force in the reference Huo et al. [1] was 3700 kN and the maximum axial
force was 4900 kN. In addition, during the earthquake the maximum shear force was about 884.15 kN,
while the calculation result is 730 kN by Gustavo et al. [2], so it can be seen that this FE numerical
simulation has high accuracy.

| Contents               | FE model | Reference | Difference (%) |
|------------------------|----------|-----------|----------------|
| $F_N$ (kN)             | 3354.64  | 3700      | -9.33%         |
| $F_{N,\text{max}}$ (kN)| 5135.29  | 4900      | 4.80%          |
| $F_{S,\text{max}}$ (kN)| 884.15   | 730       | 21.12%         |
| $d_{\text{max}}$ (cm)  | 3.275    | 3.8       | -13.82%        |

Note: $F_N$, $F_{N,\text{max}}$ are static axial force and maximum axial force, respectively; $F_{S,\text{max}}$ are maximum dynamic shear
force; $d_{\text{max}}$ is the maximum horizontal distortion of the central column.

3. Failure mechanism of composite structure

It can be seen from Figure 3 that during the earthquake the maximum value of the dynamic axial force
increased by 53.1% compared with the static axial force of the central column. Because the design cross-
sectional area of the central column is small the central column first undergoes shear failure, which leads
to the collapse of the overlying soil, it can be concluded that the RC structure shows insufficient seismic
capacity in the simulation.

![Figure 3. Axial force and shear force in central column.](image)
The central column of Daikai Station has been replaced by the CFST columns. The dynamic response simulation analysis of the CFST subway station under earthquake action was performed, and the simulation results were compared with that of the RC structures. To improve the bearing capacity of the central columns, the CFST column with the same diameter as the beam width, namely 800mm, is used, in which the thickness of the steel tube is 15.1mm. The density of the steel pipe is 7800kg/m³, the elastic modulus is 200GPa, and the Poisson's ratio is 0.26.

The deformation of the steel-concrete composite structure under the coupling action of horizontal-vertical ground motion is shown in Figure 4 [8]. Under the action of earthquake, the deformation of the composite structure is much smaller than the RC structure; the deformation of the structure is not large at the time of the acceleration peak (5.2s), and there is no obvious structural deformation after the acceleration peak. This indicates that the deformation of the steel-concrete composite structure is basically elastic deformation, with less residual deformation.

![Figure 4](image)

By extracting the horizontal distortion time history curve of the CFST column and comparing it with the above-mentioned RC column, it can be found in Figure 5 that the maximum horizontal displacement of the CFST column is 1.25cm under the horizontal-vertical ground motion coupling, the horizontal displacement deformation of CFST column is always much smaller than that of RC column.

![Figure 5](image)

The following table shows the story drift angles between the left and right walls at the peak acceleration time (5.2s) of the composite and the RC structure. Under the horizontal-vertical ground motion coupling, the story drift angle of the composite is smaller than the ordinary RC structure. This indicates that the seismic performance of the composite structure station is 46% higher than that of the RC structure station.
Table 2 Comparison in the story drift angles of composite structure and RC structures.

| Comparison index | θ\textsubscript{Com} | θ\textsubscript{Con} | θ\textsubscript{Com}/θ\textsubscript{Con} |
|------------------|----------------------|----------------------|-----------------------------|
| Left wall        | 1/574                | 1/307                | 0.535                       |
| Right wall       | 1/562                | 1/305                | 0.543                       |

Note: θ\textsubscript{Com}, θ\textsubscript{Con} are the story drift angles of the composite and reinforced concrete structure.

4. Conclusions

In this paper, the FE model is used to simulate and analyze the seismic damage response of the Daikai Station under the Hanshin earthquake, revealing the response characteristics of subway stations with different central columns.

1. An FE model of Daikai Station was established, and benchmarked by the results collected from literature, with limited difference between the predicted and collected results.

2. The central column of Daikai Station is one weak part in the structure. The horizontal-vertical coupled ground motion increased the maximum axial force of the central column by 53.1% compared to the static axial force, and this caused crushing damage at the bottom of the central column and resulted in the destruction of the entire structure and the collapse of the overlying soil.

3. The horizontal distortion of the central column of the composite structure is much smaller than that of the RC structure, and the maximum horizontal distortion of the CFST central column is 38.1% that of the RC column. At the peak of ground motion acceleration, the story drift angles of the side wall of the composite structure is about 46% smaller than that of the RC structure. This shows that the seismic performance of the composite structure has been significantly improved, so the central column is very important in the structural seismic design.

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