Shaking table test and numerical analysis of a new method for disaster control and reinforcement of frame structure crossing ground fissures

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Abstract: In order to seek suitable reinforcement measures for disaster control of structures spanning the ground cracks in high-intensity areas, a shaking table test of a five-story frame structure model spanning the ground cracks and being supported was designed according to the scale of 1:15. ABAQUS software was used to establish the calculation model of the frame structure before and after reinforcement, and the results were compared with the results of the shaking table test. The reinforcement model was analyzed from the dynamic characteristics, acceleration, displacement and strain of the structure. Therefore, the proposed disaster control and reinforcement method is feasible. The results of this study can provide a reference for the reinforcement of this kind of straddle-crack structure.

1. Introduction

Ground fissure was a discontinuous or discontinuity phenomenon of a geotechnical medium developed on the surface of the earth's crust. It was a trace of surface rupture caused by factors such as internal and external forces in the rock and soil layer and human activities[1]. Ground fissures exist in many countries and were widely distributed. China only conducted incomplete statistics on seven provinces of Hebei, Shanxi, Shandong, Jiangsu, Shaanxi, Henan, and Anhui. It has been found that more than 2010 counties (cities) have ground fissures. More than 700 locations, mainly distributed in the rift basins near several structural fault zones in North China, namely the Fenwei graben system, the Tanlu fault system, the North China plain graben system and the Dabie Mountain northern margin fault zone, the most typical of which were Ground fissure zone in Fen-Wei Basin[2]. Many scholars have conducted experiments and finite element simulation analysis on ground fissures, and have achieved some important results[3-8]. The research results were mainly focused on the characteristics of ground fissures, the formation mechanism and the dynamic response of the ground fissure site. There were relatively few studies on ground fissure structure disaster control measures. Therefore, it was of great theoretical significance and practical engineering value to carry out shaking table tests and numerical analysis studies on disaster control measures across ground fissure structures.

In this paper, taking Xi’an ground fissures as the research background, combined with engineering examples, according to the principle of reinforcement and reinforcement method, referring to Xiong Zhongming[9], the shaking table test study on the RC frame structure with cross-ground fissures was carried out. Calculation. A new type of disaster control and reinforcement measures across the ground fissure structure was proposed to provide reference and reference for urban engineering construction in the ground fissure area.
2. Reinforcement and test scheme

2.1 Experimental scheme design

The ground fissure site soil adopts the soil layer distribution near the original subway station, which was simplified according to the geological survey data. The sequence below the ground surface was ① loess, ② paleosol, ③ silty clay. The physical and mechanical indexes of each soil layer were shown in Table 1.

| Soil sample type | Moisture content/\% | Density ρ/ (g·cm⁻³) | Void ratio e₀ | Poisson's ratio μ | Shear modulus G/MPa |
|------------------|---------------------|----------------------|---------------|-------------------|---------------------|
| Loess            | 23.5                | 1.68                 | 0.96          | 0.34              | 110.49              |
| paleosol         | 22.9                | 1.78                 | 0.84          | 0.34              | 139.45              |
| silty clay       | 25.2                | 1.90                 | 0.76          | 0.34              | 163.34              |

The test was carried out in the structural seismic Laboratory of Xi'an University of architecture and technology. The shaking table adopts the 4 m × 4 m three-dimensional six degree of freedom shaking table trigger system produced by MTS company of the United States. The test model was a frame structure crossing the ground fissure after the support reinforcement. The structure was 3.6 m high, with a total of 5 floors, and the floor thickness was 150mm. The foundation adopts independent foundation. The frame column, frame beam, floor and independent foundation were all made of C30 concrete. The support was approximately steel support. The angle steel was Q235, and the size was 100 mm × 100 mm × 3 mm. The model photo after processing was shown in Figure 1.

2.2 Reinforcement scheme

This paper calculates and optimizes this kind of support layout scheme, selects this kind of support reinforcement method to carry on the external support reinforcement to the frame structure crossing the ground fissure, the support uses the flat steel Q235, the size was 20 mm × 3 mm. The support was not the more the better. The frame structure was mainly shear deformation. With the increase of the number of floors, the number of supports should be reduced correspondingly. At the same time, the connection between the support and the frame structure should be firm and reliable. All supports should be arranged in the middle span of axis 0A and axis 0d of the structure. The layout plan of the standard floor was shown in Figure 2, The support arrangement was shown in Figure 3.
3. Shaking table test structure and analysis

3.1 Test phenomenon

During the shaking table test, the peak acceleration of the table surface increased step by step, and it was subjected to seven loadings in sequence. The test phenomena and damage of the reinforced frame structure that crosses the ground crack were summarized as follows:

After the first-level loading, there was no obvious change in the structure. There were no abnormalities in the beams, columns and supports of each layer, and the structure remains intact. After the second-stage loading, slight vertical cracks appeared in local locations, and small cracks appeared in the middle span of the first layer of the upper wall, which extended along the length of the beam. After the third-level loading, there were slight vertical cracks in the corner column and middle column of the second layer, and cracks along the length of the beam appeared in the middle span of the first layer of the bottom plate of the 4th axis. After loading in the fourth and fifth levels, the first layer of the 4th axis of the upper wall extends along the cracks after the second level loading to the adjacent span. After the second-layer corner column undergoes 0.2 g, 0.3 g and 0.6 g, the cracks gradually become larger. After the sixth-level loading, the cracks in the middle span slab of the lower wall 4 axis continued to expand along the cracks after the third-level loading, and the cracks also appeared in the second-story middle span floor. In summary: during the progressive loading of seismic waves, the reinforced frame structure straddling the ground fissures had slab edge failures on the 1st and 2nd layers of the 4th axis and the 4th axis, and fewer cracks occurred at the beam-column joints.

After the test was completed, the rectangular frame of the soil box was lifted out in layers, and the layer of soil was excavated at the same time, and the ground crack propagation and trend change of the model soil were observed from top to bottom. After many vibrations, the ground fissures have expanded transverse joints at the elevation position of the base plate of the model structure (frame structure elevation -0.15 m, 1.35 m from the bottom of the earth box), which extend along the direction of the ground fissure upper wall. A slight deviation occurred and the crack width increased to 3 cm.

3.2 Analysis of support strain response

According to the measured results of the strain gauges, the results of the statistical strain amplitudes are shown in Figure 4. In order to analyze the strain of the test model supported by the earthquake, the above measurement points were selected to study the support of the ground cracks along the height of the structure. The variation law of strain amplitude and one layer of support strain amplitude. Figure 4 was the distribution curve of the strain amplitude of the Jiangyou wave, EL-Centro wave and bedrock wave across the ground fracture under the same peak acceleration seismic wave along the floor height.
When the peak acceleration was 0.2 g, the support strain amplitudes of the first and second layers were larger than those of the other layers, the strain amplitudes of the third and fifth layers were less than those of the fourth layer, and the strain amplitude of the fifth layer was the smallest. Under the action of the three waves, the amplitude of the supporting strain was basically equal in the first layer and the top layer, and the strain amplitude in the other layers was separated. The strain amplitude caused by the Jiangyou wave was larger, followed by the EL-Centro wave, and the bedrock wave was the smallest. When the peak acceleration was 0.4 g and 0.6 g, the strain amplitude increases with the increase of the ground motion. Under the action of Jiangyou wave and EL-Centro wave, the strain amplitude of the second layer increases greatly, more than one layer; Under the bedrock wave, the strain amplitude of one layer was greater than that of the second layer. When the peak acceleration was 0.8 g, the strain amplitude of the second layer was greater than that of the first layer under the action of three waves.

![Figures](4) Distribution of strain amplitude across ground fissures

### 4. Experimental numerical simulation of shaking table

#### 4.1 Model overview

The three-dimensional model of the soil and frame structure of the shaking table test model was numerically simulated. The length of the site soil was 45 m, the width was 22.5 m, and the thickness of the soil was 22.5 m. The layout was the same as the shaking table test. The soil constitutive model Select the Mohr-Coulomb constitutive. The normal action of ground fissures was set to hard contact, and the tangential action was simulated by setting Penalty, the friction coefficient was 0.3, and the boundary conditions were viscoelastic artificial boundaries.

The constitutive model of slab concrete of frame structure adopts plastic damage model. The relationship between constitutive materials of superstructure beam-column concrete and reinforcement was shown in Figure 5 and Figure 6. Specifically, the concrete constitutive model UConcrete02 considering tensile strength and damage degradation was adopted. The constitutive relation of reinforcement adopts the ideal elastic-plastic model. In addition, bilinear reinforced elastic-plastic model was used to simulate steel supports, as shown in Figure 7. The contact between the support and the structure was set as hinge.

![Figures](5, 6, 7) Constitutive relations
In order to more effectively explain that supporting the reinforcement of the structure under the action of earthquakes can effectively reduce the damage to the structure caused by the earthquake, in this paper, the reinforcement measures for the frame structure across the ground fissures were established, and the three-dimensional finite element before and after the ground fissures were strengthened. The model was shown in Figure 8. In this paper, when verifying the numerical simulation results, three operating conditions of 0.2g El-Centro wave, Jiangyou wave and bedrock wave were selected for the shaking table test of disaster control measures across the ground fissure frame structure.

![Figure 8: three-dimensional Finite element model](image)

When performing dynamic time history analysis, it was considered that the system error of the vibration table will cause the difference between the reproducible value of the ground motion of the table and the expected value. Therefore, the acceleration input at the bottom of the soil was selected from the measured acceleration of the vibration table, but the acceleration time history collected by the table cannot be directly used for simulation, and it needs certain processing. First, delete the invalid data before and after.

### 4.2 Experimental verification of numerical simulation

#### 4.2.1 Comparison of top-level acceleration time-history curves

It can be seen from Fig. 9 that by comparing the top-level acceleration time-history curves, it was found that under the action of the three waves, the simulated top-level acceleration time-history curves overlap well, and there was a lag phenomenon compared with the experiment, and the duration of strong earthquakes was basically the same.

![Fig.9 Time history curves of acceleration at the top layer under different seismic waves](image)

It can be seen from Table 2 that under the action of the three waves, the numerical simulation results show that the top acceleration peak was different from the test peak acceleration, but the gap was not very large. The top acceleration peak simulation results were smaller than the test results, and the top layer acceleration response was the larger the operating conditions, the second the EL-Centro wave, and the smallest bedrock wave, indicating that the acceleration response obtained by the test and
the numerical simulation was consistent. It can be seen that the simulation results of the model established in this paper have a certain accuracy, which lays the foundation for the numerical analysis later.

Table 2 Comparison between numerical results and experimental results of peak acceleration on the top floor /g

| Seismic wave       | After reinforcement | The relative difference |
|-------------------|---------------------|-------------------------|
|                   | The test results    | Simulation value        |
| Jiangyou wave     | 1.411               | 1.188                   | 0.224                   |
| EL-Centro wave    | 1.151               | 0.829                   | 0.323                   |
| Bedrock wave      | 0.889               | 0.786                   | 0.102                   |

4.2.2 Model 1 layer support strain verification

Table 3 shows the magnitude of the supporting strain of the model under the action of the peak acceleration of 0.2 g Jiangyou wave, EL-Centro wave and bedrock wave. Z1, Z12, Z13, Z14, Z15 and Z16 in the table correspond to the test points. It can be seen from Table 3 that the peak strain Z12 across the ground fracture supports was greater than the upper plate Z11 and the lower plate Z13, the upper plate Z11 was larger than the lower plate Z13, and Z15 was smaller than the upper plate Z14, and Z14 was smaller than the lower plate Z16. It shows that the support strain response caused by the ground fracture site at the A axis crossing the ground fissure was larger and the lower wall was smaller, while the support strain response at the D axis across the ground fissure structure was larger and the support response across the ground fissure was smaller the peak response of Jiangyou wave was the largest, followed by EL-Centro wave, and the bedrock wave was the smallest. It can be seen from the simulation results that the support layer's variation law was consistent with the experimental variation law.

Table 3 The first support strain of the first layer/μƐ

| Working condition | Ashaft support | Dshaft support |
|-------------------|----------------|----------------|
|                   | Z11 | Z12 | Z13 | Z14 | Z15 | Z16 |
| Jiangyou wave     | 385 | 689 | 151 | 276 | 55  | 69  |
| EL-Centro wave    | 302 | 668 | 97  | 152 | 33  | 79  |
| Bedrock wave      | 149 | 632 | 56  | 93  | 37  | 44  |

5. Conclusion

Based on the shaking table test of disaster control measures across the ground fissure structure, this chapter uses ABAQUS finite element analysis software to establish the model before and after the reinforcement of the cross-fracture frame structure, and compares the calculation results with the shaking table test results. Good consistency. At the same time, the comparative analysis of the seismic performance of the two models before and after reinforcement from the aspects of interlayer displacement, top layer acceleration and floor shear strength finds that the reinforcement method proposed in this paper was feasible, which can effectively reduce the ground cracks on the superstructure Destroy and draw the following conclusions:

(1) By comparing the first three orders of natural vibration frequencies before and after strengthening the ground crack frame structure, the stiffness of the strengthened frame structure across the ground crack was increased.

(2) By comparing the peak acceleration of the top layer before and after the reinforcement of the ground fissure frame structure, it was found that under the action of earthquakes, the support of the reinforced cross-fracture frame structure effectively reduces the top layer acceleration response of the frame structure on the ground fissure site.

(3) The support strain of the model is analyzed, and the study shows that the peak strain response of the jiangyou wave was the largest, followed by the El-Centro wave and the bedrock wave is the
It can be seen that the variation law of the simulated result of the support layer was consistent with that of the test.

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