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Experimental study of a segmented metro tunnel in a ground fissure area

Nina Liu[a,b,*], Qiangbing Huang[a,b], Yujie Ma[a,b,c], Rifat Bulut[d], Jianbing Peng[a,b], Wen Fan[a,b], Yuming Men[a,b]

[a] School of Geological Engineering and Geomatics, Chang'an University, Xi'an 710054, China
[b] Key Laboratory of Western China's Mineral Resource and Geological Engineering, Ministry of Education, Xi'an 710054, China
[c] Xi'an China Highway Geotechnical Engineering Co. Ltd., 710075 Xi'an China
[d] School of Civil & Environmental Engineering, Oklahoma State University, Stillwater OK, 74078 United States

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ABSTRACT

This paper studies the seismic response of a segmented metro tunnel with flexible joints passing through active ground fissures in Xi'an by shaking table model test. A coupling dynamic ground motion was generated in the test model. The tunnel acceleration, earth pressure and tunnel structure strain were monitored and compared. It was observed that each part of the tunnel has an independent movement with flexible joints. The tunnel located in the hanging wall has 3.17 times peak acceleration than that in the foot wall. Higher magnitudes of earth pressures were recorded close to the areas of the ground fissures. The earth pressure in the hanging wall was greater than that in the foot wall. The coupling loads increase the earth pressure. The strain in the middle of the tunnel arch was the largest. The strain at the bottom of the floor was the secondary. The one on the top of the arch was the smallest. The strain increased less in each section because the tunnel is divided into four parts by flexible joints, and no sharp strain increase close to the ground fissure was observed. The results indicate that the flexible joints can decrease the stress concentration. The tunnel with flexible joints can adjust to large deformations in the ground fissure areas.

1. Introduction

Ground fissures are geological hazards and have been found in many parts of the world including the United States, China, Australia, and in some countries in Africa. In the United States, the ground fissures were found in the late 1920s at the Goose Greek oil field near Houston, Texas. In China, the earliest ground fissures were found at the end of 1950s [1–4]. The ground fissures pose serious restrictions on urban planning and construction. In some parts of China, the ground fissures have been a major geological hazard. In the provinces of Shandong, Anhui, Jiangsu, Shanxi, Shaanxi and Henan, the ground fissures have caused serious disasters to buildings, roads and pipelines. These ground fissures have high geo-hazard potential and influence the city planning. Most ground fissures in China are still active [4–16].

Xi'an is the capital city of Shaanxi province with a population of over 8 million, and is the center of industry and business in west China. The total number of ground fissures have been discovered in Xi'an is up to 14 since 1950s. The total length of the current ground fissures is over 100 km with a coverage area up to 150 km^2 in 2013 [9,10]. The active ground fissures pose serious restrictions on the urban planning in Xi'an.

Many studies have been carried out and many useful results have been obtained in the literature. For the formation mechanisms about the ground fissures, there were two different opinions. The first opinion is that the ground fissures are induced by the over pumping of groundwater [3,6,11]. The second opinion considers tectonics movements for the main reason behind the formation of the ground fissures [4]. In the current literature, a consensus has gradually formed that the tectonics determine the distribution of ground fissures, and the pumping of the groundwater is a direct cause of the major activities of the ground fissures. This opinion has been accepted by more researchers recently [1,2,9,10].

For the urban planning, the Xi'an Metro was initially designed as part of a multi-level transportation system. There are fifteen planned metro lines in Xi'an, and among those Metro I , II and III have already been constructed and are in operation, and the Metro IV & V are under construction. Metro tunnels are usually constructed on linear routes and, therefore, it is hard to avoid all the fourteen ground fissure areas in the complex geology environment of the Xi'an city. For example, the Metro Tunnel I crosses 5 ground fissures with 8 intersections, the Metro Tunnel II crosses 10 ground fissures with 12 intersections, and the Metro Tunnel III crosses 8 ground fissures with 15 intersections.

In order to find efficient and safe methods to design and build

* Corresponding author at: School of Geological Engineering and Geomatics, Chang'an University, Xi'an 710054, China.
E-mail address: dcdgx16@chd.edu.cn (N. Liu).

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tunnels in these special sites with so many ground fissures, a systematic research has been applied for several decades. The research methods include survey on site, theoretical analysis, numerical modeling and physical simulation experiments. Before 2007, the research focused on geological characteristics such as the original cause, distribution and development regularities. Based on the results from this period, the following research studies have paid more attention to the mechanism of construction characteristics which are located in the ground fissure areas.

The series of the research studies have found that the uneven settlements caused by the vertical movement of the hanging wall would lead to damage to the metro tunnel. In order to find an effective countermeasure for the safe design of the metro tunnel against the ground fissure damage, a series of prototype model tests of the metro tunnel with flexible joints were considered for the Xi'an Metro design [9,10]. The results of these research studies indicate that with the flexible connection, the tunnel had more ability to adopt large deformations and to avoid high stress concentrations.

The Xi'an city is located in the Fen-Wei basin which is known as the taphrogenic belt, and many destructive earthquakes have occurred in this region and certain seismic activities still exist. In order to analyze the metro tunnel features and mechanisms, a physical simulation experiment was undertaken to study the rupture propagation characteristics of the ground fissures and the response mechanisms of the metro tunnel such as the acceleration, the stress, and the strain, which are all important parameters for understanding the development of the ground fissures and the metro tunnel design in these geo-hazard areas.

The shaking table is a common testing method for studying seismic performance of underground structures [16–18]. It has been used to conduct the dynamic response and failure mechanisms of tunnels under various seismic activities. Based on the input ground motions, the shaking table tests have two kinds of vibration characteristics-simple harmonic vibrations and simulated earthquake vibrations [19]. In the shaking table tests, the flexible, shear stack or rigid containers have usually been utilized for simulating different boundary conditions [20]. In recent years, the geotechnical centrifuge has been used in the physical modeling of the problem to investigate the effects of normal faulting on shallow segmental tunnels [21]. For the improvement of the physical models, the geotechnical centrifuge and shaking table may be utilized together for the dynamic centrifuge tests [22]. While the shaking tables are quite sophisticated in handling a wide range of simulated ground motions, they are relatively easy to control and can automatically record and store data. These shaking tables cost less as compared to some other experimental methods. In this study, the shaking table is employed to analyze the seismic response of a segmented metro tunnel in a complex ground fissure area. The segmented metro tunnel is influenced not only by the seismic activities but also by the movement of the ground fissures due to complex underground geology conditions; therefore, dynamic tests can provide insight into the understanding of the segmented metro tunnel-soil stress-strain behaviors [23–25].

The objective of this paper is to analyze and evaluate the dynamic response of a segmented metro tunnel with flexible joints located in an area with ground fissures using the results from a shaking table test. The segmented metro tunnel is simulated by fine aggregate concrete. The resulting dynamic behavior of the tunnel was observed along with the recorded accelerations in each segment. The earth pressure and strain measurements were compared in each segmented tunnel. The study indicates that this method of design can reduce the geo-hazard potential of ground fissures.

2. Ground fissure characteristics

2.1. Ground fissure movement characteristics

The formation mechanism of the ground fissures in the Xi'an region is based on the excessive pumping of groundwater, which has activated the underlying Chang'an–Lintong fault and caused instability to the surface layer [10]. The Chang'an–Lintong active fault determines the spatial distribution of the Xi'an ground fissures. The activity characteristics of the 14 ground fissures are determined by the active fault and pumping of the groundwater. The 14 ground fissures are banding distributed with the distance between each pair varying from 500 m to 1500 m. Most of the fissures strike toward NEE with an angle about 70°. In the cross-section, the deformation characteristics of the 14 ground fissures exhibit a synchronous decrease in the hanging wall. The deformation zone can be divided into the major deformation zone and the minor deformation zone. More closer to the surface, the deformation is larger. The width of the major deformation zone is usually 5–15 m. The minor deformation zone is generally 20 m on the hanging wall and 10 m on the foot wall.

The 14 ground fissures in the Xi'an region have a three-dimensional movement characteristic, as the vertical settlement, the horizontal extension and the horizontal twisting. The ratio of the three movements is 1:0.30:0.03. The results of the research study show that the horizontal extension is caused by the uneven settlement between the hanging wall and foot wall. The horizontal extension decreases with depth. The values of the horizontal extension and horizontal twisting are minimal at the depth of 10 m where the metro tunnel is mostly underground. The influence of the ground fissures on the metro tunnel is controlled by the vertical displacement.

Due to the extraction of the groundwater, the 14 ground fissures in the Xi'an region have been active since the end of the last century. The rate of the vertical settlement is about 10–40 mm/year, with a maximum value of 56.93 mm in 1996. Since 1996, the exploitation of the groundwater has been restricted in Xi'an. As a result, the movements in the 14 ground fissures have decreased to about 2–15 mm/year. Fig. 1 shows the forecast and the design vertical displacement value of each ground fissure that has interaction with the Xi'an Metro II for the design period of 100 years.

2.2. Ground fissures damages to metro tunnel

Uneven settlement is the most serious reason of the stratum destruction and it leads to damages to the metro tunnel crossing the ground fissures. Fig. 2 shows the results from an experiment, in which the metro tunnel is buried in the soil at the ground fissure site, and where the hanging wall has 25 mm vertical displacement downwards when the footing wall remains at rest condition. As depicted in Fig. 2(a), the metro tunnel had descended in the hanging wall area away from the fissure. There is a disengaging zone under the tunnel in the hanging wall. Fig. 2(b) also shows the disengaging zone. The compressive and tensile stresses are shown in Fig. 2(c). The top of the

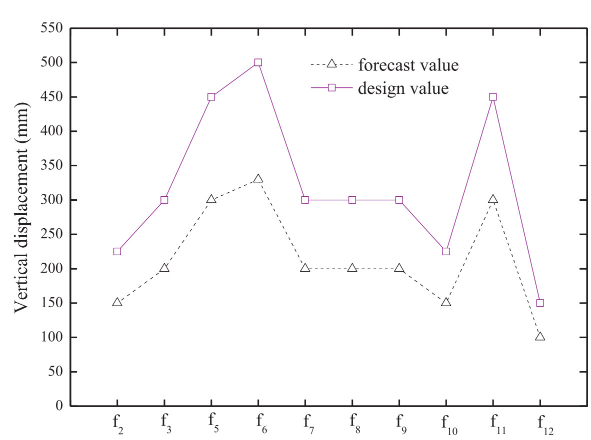

Fig. 1. Vertical displacements within the ground fissure areas.

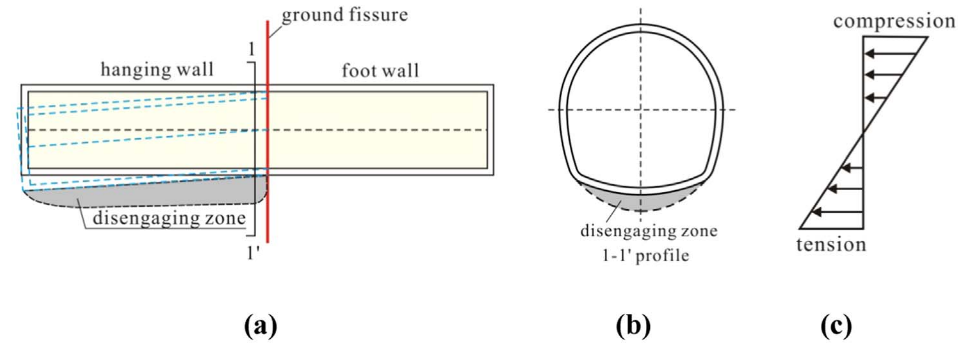

Fig. 2. Behavior of the metro tunnel crossing the ground fissure.

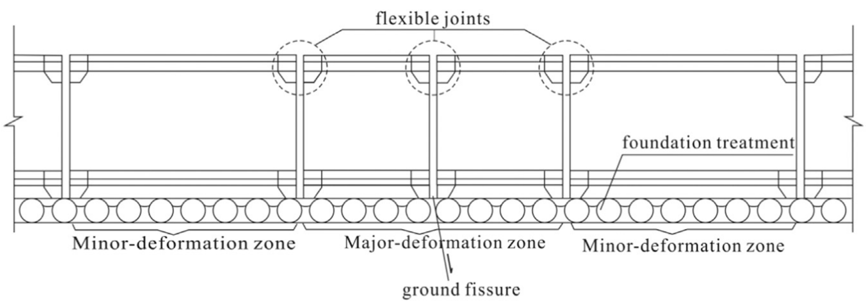

Fig. 3. Segmented metro tunnel with flexible joints.

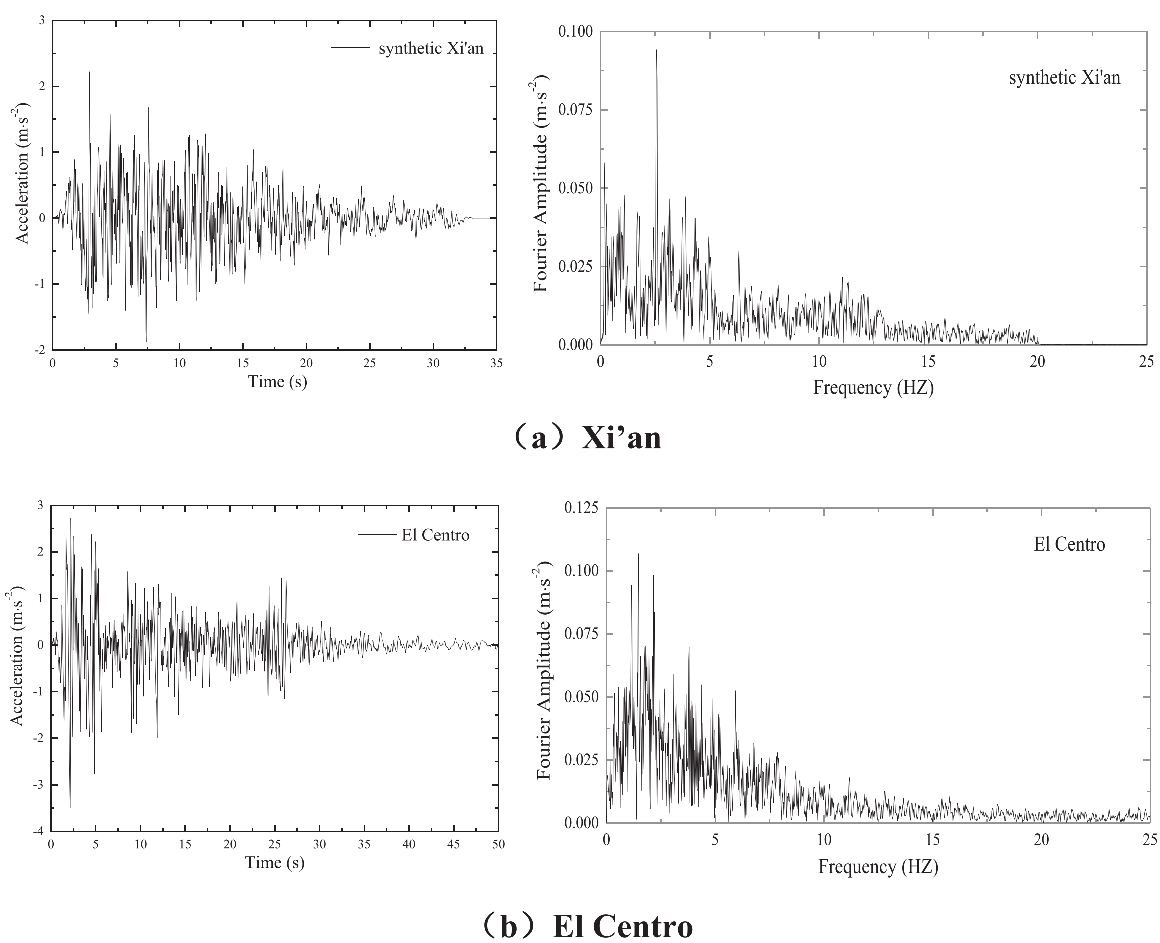

Fig. 4. Acceleration-time histories and Fourier spectra of (a) synthetic Xi'an earthquake wave, (b) El Centro earthquake wave.

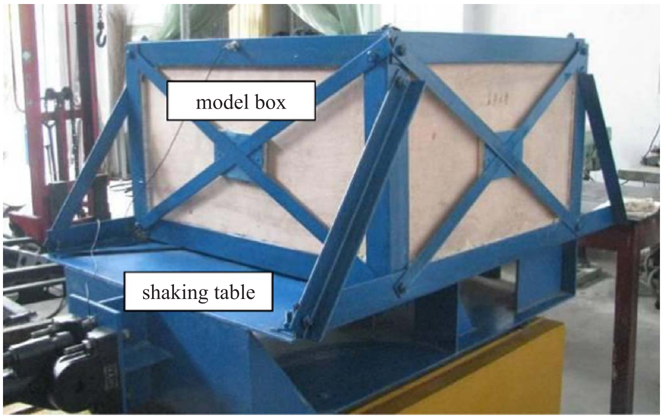

Fig. 5. Shaking table and model box.

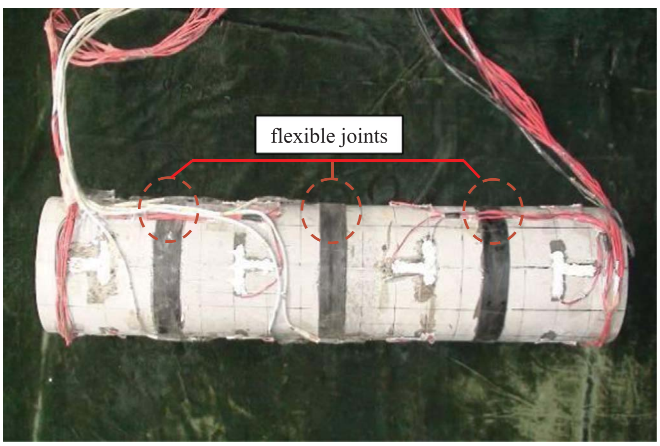

Fig. 6. Top view of segmented metro tunnel model.

Table 1
Model Parameters.

Tunnel model	Unit Weight ($kN\ m^{-3}$)	Cube strength (MPa)	Elasticity modulus (MPa)
	25.00	2.98	3.3×10^3
Flexible joints	Hardness (HA)	Tensile strength (MPa)	Elongation at break (%)
	60	5.7	270

tunnel structure in the hanging wall was under compression, while the bottom of the tunnel structure in the footwall experienced tension.

2.3. Structural measures

The design value for the vertical displacement in ground fissures is 500 mm in a 100-year period (Fig. 1). The behavior of the metro tunnel is shown in Fig. 2. The earlier studies have shown that the construction of stiff structures may not be an economical and practical solution in the areas where ground fissures exist. The effective countermeasure is to design structures that adapt to the deformations caused by the ground fissures. This study shows that the segmented metro tunnel with flexible joints can tolerate the deformations caused by the ground fissures (Fig. 3).

3. Model tests

3.1. Testing equipment

The shaking table used in this study is shown in Fig. 4. The shaking table has the following properties: the vibration frequency is from 0.1 to 50.0 Hz, allowable weight is 2000 kg, length of the table is 1.5 m, and the width is 1.0 m. For the analysis, the synthetic Xi'an earthquake wave and El Centro wave were loaded in the shaking table. The synthetic Xi'an earthquakes are in accordance with the geological characteristics of the Xi'an region. The El Centro earthquake wave was recorded in Empire Valley, U.S.A. in 1940 and is widely used in earthquake research. The seismic record of south-north direction was revised to match with the geological characteristics of the Xi'an metro site. Fig. 4 presents the acceleration time histories and Fourier spectra of the two records.

In the testing setup, the acceleration transducers were used for the measurements in the soil as well the tunnel. Miniature earth pressure cells were also utilized for measuring the earth pressure in the soil and tunnel during the earthquake generated by the shaking table. The strain gauges were used to investigate the dynamic response of the tunnel. The dynamic signal test and measurement system were utilized in the data acquisition.

3.2. Model test

A rigid model box was mounted on the shaking table for the model test (Fig. 5). The box has the dimensions of 1.0 m in length, 0.9 m in width, and 0.6 m in height. The box is made up of stiff steel frame. At the bottom of the box, wood pieces were nailed at distances of 200 mm

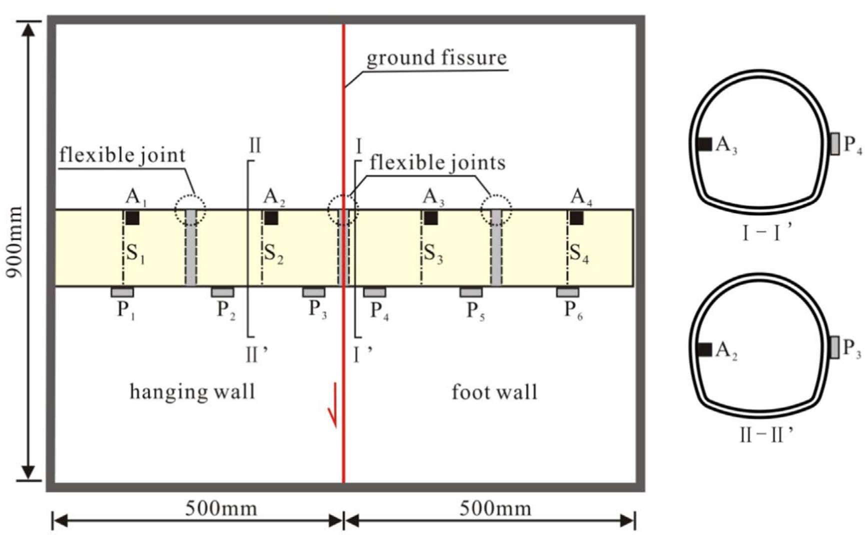

Fig. 7. Layout of testing device.

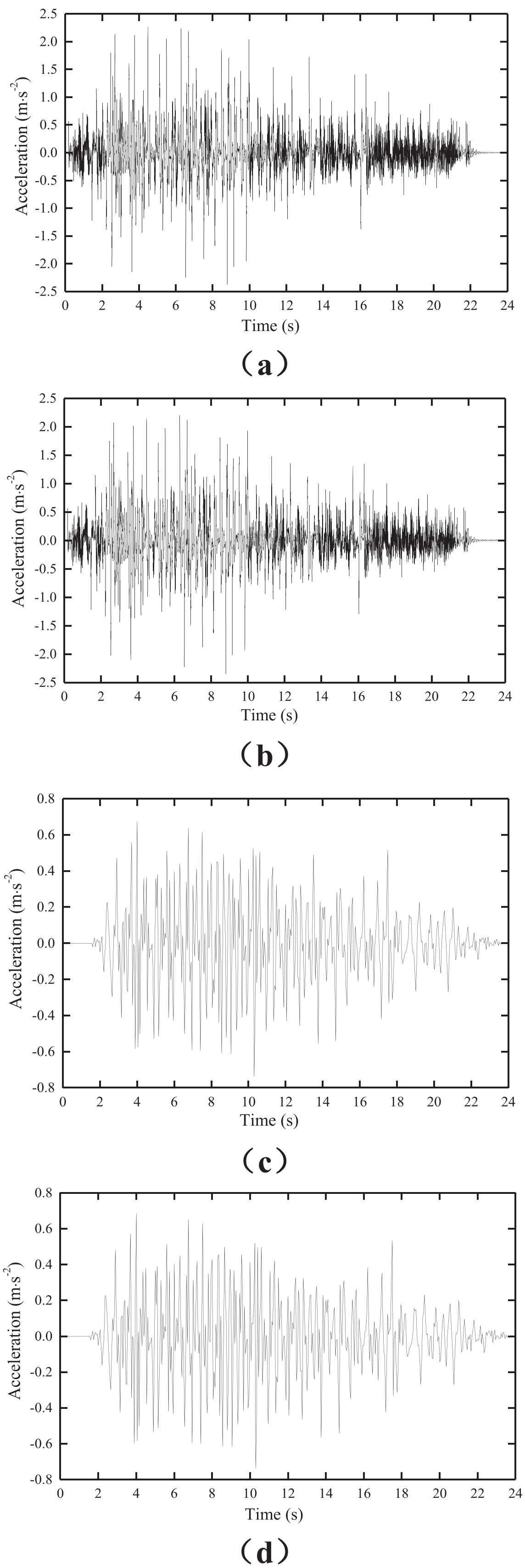

Fig. 8. Acceleration time history curves of (a) A1, (b) A2, (c) A3, (d) A4.

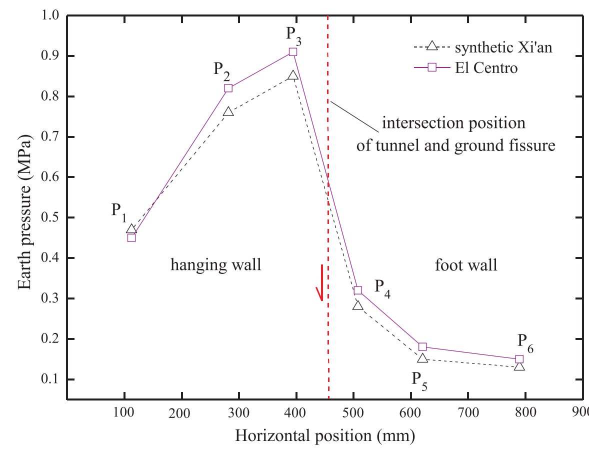

Fig. 9. Earth pressure distribution curve.

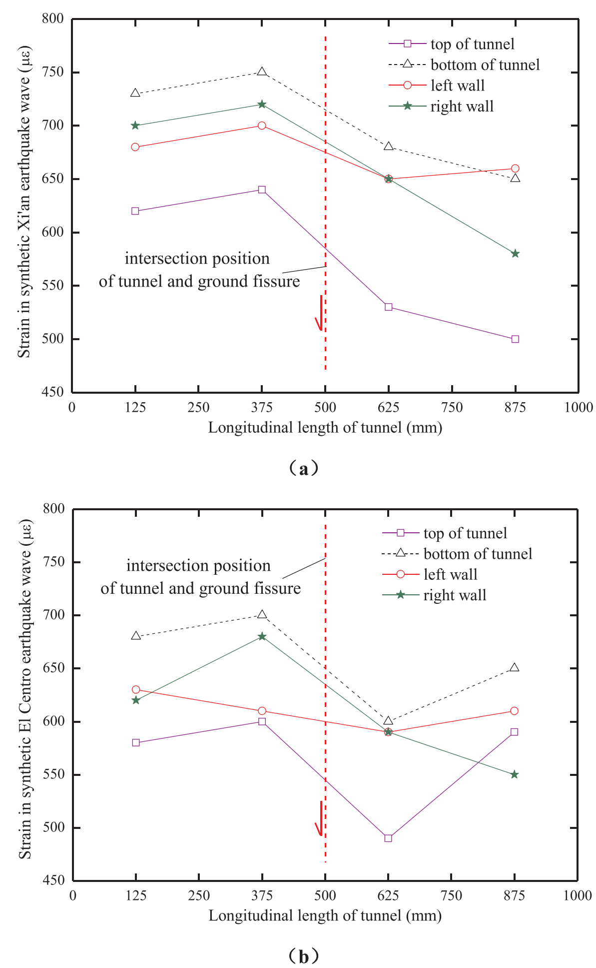

Fig. 10. Variation of strain in the tunnel of (a) Strain in synthetic Xi'an earthquake wave. (b) Strain in El Centro earthquake wave.

apart, in order to increase the friction between the soil and the bottom of the box. The prototype tunnel is made of fine aggregate concrete (Fig. 6). The parameters are given in Table 1.

Fig. 7 shows the arrangement of the model box and the testing instrument. There are four acceleration transducers inside each segment named as A1, A2, A3, A4, and six miniature earth pressure cells located along the tunnel from P1 to P6. The gages were positioned on the S1, S2, S3, S4 locations along the circumference of the tunnel, and at four points on the top, at the bottom and on both sides of the walls.

4. Test results and their analysis

4.1. Acceleration characteristics

The four acceleration transducers located in each part of the metro tunnel are shown in Fig. 6. The results from the four acceleration transducers are given in Fig. 8 for the shaking table loading mode in the synthetic Xi'an earthquake wave. The comparison of Fig. 8(a) with Fig. 8(b) shows that the acceleration time history curves are very similar and both have the same acceleration of $2.41\ \mathrm{m\ s^{-2}}$. Fig. 8(b) and Fig. 8(d) also have similar acceleration records with the same acceleration peak value of $0.76\ \mathrm{m\ s^{-2}}$. The results indicate that the two tunnel sections in the hanging wall have the same dynamic characteristics. In addition, the two tunnel sections in the foot wall also show the same dynamic characteristics when considering the synthetic Xi'an earthquake wave loading on the shaking table. However, the tunnels in the hanging wall have 3.17 times peak acceleration to the tunnel sections in the foot wall. This may indicate that the hanging wall amplified the dynamic response as compared to the response in the foot wall.

4.2. Earth pressure results

Fig. 9 depicts the earth pressure curves recorded by the six miniature earth pressure cells after the shaking table loaded with the synthetic Xi'an earthquake wave and El Centro earthquake wave. In the hanging wall, higher earth pressures were recorded close to the fissure areas. The earth pressures in the hanging wall are larger than the earth pressures in the foot wall no matter whether it is under the synthetic Xi'an earthquake wave or El Centro earthquake wave loading conditions.

4.3. Strain characteristics

Fig. 10 shows the strains in the metro tunnel for the El Centro earthquake and synthetic Xi'an earthquake wave loadings on the shaking table. From the measurement of the strains, the largest strain values in the tunnel occur in the middle of the right and left tunnel walls. The bottom of the tunnel has the intermediate strain values while the smallest strain values occur on the top of the tunnel.

The strains are not significantly influenced with the distance to fissure locations. While the hanging wall has large acceleration values and earthquake pressures, the tunnel does not show significant strain values. The strains in the tunnel are approximately equal for both in the hanging wall and foot wall. The results show that the flexible joints have some influence on the strains in the tunnel. The results also indicate that the dynamic response of the hanging wall was reduced by the flexible joints.

5. Discussions

Due to the limitations of the shaking table loading capacity, the dynamic properties were only partially fulfilled in the study. However, the model test was not affected by this problem, and the data to characterize the segmented metro tunnel with flexible joints behavior appeared to be reasonable. The responses and amplifications of the model test appeared to reflect the behavior of the prototype tunnel under seismic loading conditions reasonably well when compared to the field observations of the metro tunnel failure under the vertical displacements at the site. Thus, the response and amplification behavior of the prototype tunnel and ground fissure site can be studied in the laboratory for further evaluation of the tunnel behavior under earthquake conditions in the field. Further modifications and improvements of the testing setup can be designed to have dynamic similitude with the real application, and that in return can provide better interpretation of the results concerning the mechanics of the metro tunnel. Therefore, more prototype model tests should be developed to take into account more factors such as the details of the flexible joints and the basement of the tunnel, in order to better simulate the behavior of the segmented metro tunnel with flexible joints.

6. Conclusions

A model test has been performed to study the mechanical behavior of the segmented metro tunnel with flexible joints crossing ground fissures under earthquake activities. Acceleration responses, earth pressures and strains at different locations in the model were measured. Based on the previous discussions, some conclusions are reached as follows:

(1) With the flexible joints, each section of the tunnel has an independent dynamic movement. The tunnel located in the hanging wall has 3.17 times peak acceleration than that in the foot wall.
(2) Higher values of earth pressures were recorded close to the ground fissure areas. The earth pressure of the hanging wall is 6 times larger than that in the foot wall. The coupling loads increase the earth pressure.
(3) The strain in the middle of the tunnel arch is the largest. The strain at the bottom of the floor is the secondary. The strain on the top of the arch is the smallest. The strain increased less in each section because the tunnel is divided into four parts by flexible joints, and without any sharp strain increase close to the ground fissure.

The results indicate that the flexible joints can decrease the stress concentrations. Therefore, the tunnel with flexible joints can tolerate large deformations in the ground fissure areas.

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