A Large-scale Static-dynamic Model Test System for Stability Study of Tunnel under Static-dynamic Load

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Abstract

In order to study the stability of tunnels under static-dynamic load, a new large-scale static-dynamic model test system was developed. The system is composed of a static loading unit, a dynamic loading unit, a data acquisition unit and a test bench, which are specially designed to overcome the technical problems of large-scale static-dynamic model test, such as dynamic loading and control, high-rate strain measurement and easy operation. The system uses a model of $3600 \times 3600 \times 2500$ mm in size to study a larger load disturbance area than static tests. It can accurately apply three-dimensional gradient static stress and dynamic load with adjustable amplitude (or magnitude), frequency and waveform to simulate the true geo-stress field and disturbance field, and accurately and rapidly collect displacement, stress, strain, velocity, acceleration and other important parameters of the model. In addition, it is convenient to adjust the scale of the model, remove and retain the test model. The system was used to carry out a static load model test and a static-dynamic load model test with a tunnel as a prototype, and its reliability and accuracy were verified.

1. Introduction

In tunnel construction, complex geological and hydrological conditions are often encountered (Sharafat et al. 2021; Pourhashemi et al. 2021). In this case, the stability of surrounding rock is poor, the support is difficult, and the cause of disasters and the catastrophic process are complex, which seriously threatens the safety of tunnel (Panthi and Basnet 2021; Song et al. 2021). Mastering rock response during the excavation of tunnel can effectively guide tunnel design and construction (Satici and Topal 2021). Geo-mechanical model test is one of the most effective means to investigate the problem because of its controllable test conditions, easy repetition of construction process and easy data acquisition (Zhang et al. 2016; Lin et al. 2021).

Model test system is the premise of geo-mechanical model test. In recent years, many model test devices have been developed for stability analysis of tunnel surrounding rock. Li and Zhang (2014) developed an experimental table for plane strain model test of tunnel construction. Li et al. (2013b) developed a model test system to study the mechanical regularity of the Tianpingshan Tunnel during construction process. Chen et al. (2015) developed a servo controlled gradient loading model test system to simulate the gradient geo-stress in deep-buried cavern. Li and Wang (2014) and Li et al. (2016) developed an extendable testing system modelling water inrush in subsea tunnel to investigate the fault at the undersea tunnel in Jiaozhou Bay near Qingdao. Lin et al. (2015) developed a geo-mechanical model test system to investigate the failure behaviour and instability of the “large, deep, long and in-group” tunnels. Hu et al. (2019) developed a geo-mechanical model test system for the study of motion laws of rock falls on heading slope of tunnel and the responses of the open-cut tunnel structure to the impact. Liu et al. (2019) developed a three-dimensional assembled large-scale geo-mechanical model test system for the study of excavation process of a super-large section and a shallow-buried tunnel with a small space. Zhang et al. (2021) developed a hydro-mechanical coupled geo-mechanical model test system to study

the surrounding rock stability, water inrush mechanism and support control of the deeply buried tunnel under hydro-mechanical coupling.

In summary, the existing model test system in tunnel engineering can only apply static load, but cannot apply dynamic load (Zhang et al. 2020). Therefore, these test systems cannot be used to study the dynamic response of tunnel surrounding rock under dynamic loads such as drilling, blasting and crustal movement.

Compared with the static load, the static-dynamic load has a greater threat to the safety of the tunnel (Tsinidis 2017; Li et al. 2020). The dynamic action can increase the stress of the rock mass under the ultimate stress, break the original equilibrium state, increase the displacement of the key point and expand the plastic zone of the tunnel surrounding rock etc. (Li and Li 2018; Yang et al. 2018). It is very necessary to study the dynamic response of underground structures under static-dynamic action. Therefore, a new large-scale static-dynamic model test system was developed, which can be used for static load model test, dynamic load model test and static-dynamic load model test.

2. Development Of The Model Test System

The development of static-dynamic load model test system is very difficult. Firstly, dynamic load test has the characteristics of high strain rate, and inertia and wave propagation effects are more obvious than quasi-static test (Zhang and Zhao 2014). This means that the dynamic load model test should have a larger model scale than the static test. Secondly, static-dynamic test involves dynamic loading technology and high-rate deformation measurement technology. Finally, the safety and convenience of the test should be considered.

Therefore, each part of the system is specially designed. As shown in Fig. 1, the model test system includes a test bench, a static loading unit, a dynamic loading unit and a data acquisition unit. The test bench is the main frame of the test system and the place where the model is made, and it also has the function of providing reaction force for static loading. Static loading unit and dynamic loading unit respectively impose predetermined static and dynamic loads on the model to simulate the real in-situ stress field and disturbance field. Data acquisition unit is used for high-rate acquisition and recording of key information in the model during the test.

2.1 Test bench

In the design of test bench, the feasibility and convenience of large-scale model test are mainly considered. As shown in the Fig. 2, the model bench is designed in combination. It consists of five 0.5 m thick portal reaction frames, a visualized front reaction beam, a rear reaction beam, a visualized excavation window and a model moving system. By adjusting the number of frames, a test model of $3600 \times 3600 \times (500-2500)$ mm in size can be obtained (Fig. 2(a)). The front and rear reaction beams are all composed of six identical beams, which are easy to assemble. All reaction beams and frames adopt ribbed structure and can be embedded with hydraulic cylinders. The structure not only guarantees the

reaction bearing capacity of the test bench, but also reduces the external size of the test system. The front reaction beam adopts hollow structure and can be embedded with tempered glass to realize visual monitoring of the front of the model. The middle part of the rear reaction beam can be separately dismantled to simulate the synchronous two-way excavation and combined excavation of the tunnel (Fig. 2(b)). The model moving system can remove the test model by hydraulic drive, which facilitates the extraction and retention of large-scale test model and improves the test convenience. Its structure is shown in Fig. 2(c), the vertical cylinder is used for the jacking of the model, and the horizontal cylinder is used for horizontal movement of the model.

2.2 Static loading unit

In the design of static loading unit, stress field similarity, loading accuracy and control convenience are considered. The unit mainly includes a software system, a hydraulic control system and several hydraulic cylinders. Its working principle is shown in Fig. 3. The cylinders are installed at the top, left, right and back of the model bench to simulate the real three-dimensional stress field. The cylinders on both sides are divided into six loading areas, each of which is independently controlled by one oil circuit to obtain gradient stress fields similar to those in the field. The setting, adjustment and monitoring of static loading and unloading are all implemented by software to increase the convenience of the test. High-precision stress control is realized by the control loop formed by pressure sensors and control system.

2.3 Dynamic loading unit

The design of dynamic loading unit focuses on the loading accuracy of dynamic load and the convenience of control. The working principle of the dynamic loading unit is shown in Fig. 4. The unit controls the vibration generator through the cooperation of operation software, dynamic automatic control system and control unit, and collects real-time feedback parameters such as pressure and displacement of the vibration generator to realize the high precision control of dynamic load. A force transfer block is installed on the piston rod of the vibration generator to exert dynamic load on the test model. Tracks can be placed between the load transfer block and the test model to simulate the dynamic loads of high-speed trains. The magnitude of dynamic load applied by this unit is 0-500 kN, the frequency is 0.1–50 Hz, the amplitude is 4 ± 2 mm, and the waveforms are sinusoidal, triangular, square and random. And these parameters can be set and monitored by software.

In order to ensure the accuracy of dynamic loading, the dynamic loading unit also needs the cooperation of reaction frame with high stiffness. The structure of dynamic loading reaction frame in this system is shown in Fig. 5. This structure is the optimum structure obtained by design and calculation. Its characteristic is that the top beam adopts fish-belly structure. Under the dynamic load of 10 Hz and 500 kN, the dynamic loading reaction frame has a maximum displacement of only 1.128 mm, which meets the test requirements (Li et al. 2013a). The reaction frame is bolted to the outside of the static load reaction system. There are isolation grooves between them to prevent the influence of dynamic load on the model bench.

2.4 Data acquisition unit

Quantitative acquisition of dynamic mechanical properties and deformation fields largely depends on data testing techniques (Zhang and Zhao 2014). Therefore, the self-developed mini-grating displacement measuring system and dynamic signal measuring system are selected as the components of the data acquisition unit. Among them, the mini-grating displacement measuring system is used for the measurement of absolute displacement, and the dynamic signal measuring system is used for the measurement of acceleration, velocity, stress, strain and other parameters. The two systems have the characteristics of high acquisition frequency, high resolution and strong anti-interference ability. They can be used in both dynamic and static tests.

The mini-grating displacement measuring system consists of a grating data acquisition instrument, a grating ruler, an extensometer, and other related accessories (Li et al. 2017). The extensometer is a specially designed structure, which can accurately transmit the absolute displacement of the measuring point to the grating ruler. The grating ruler is a displacement sensor based on moire fringe, which has the advantages of high precision (resolution up to $0.1\mu\text{m}$), high rate and not affected by external electromagnetic field. It can convert displacement signal into electrical signal and transmit it to grating data acquisition instrument. The grating data acquisition instrument is used for the acquisition of displacement signals. It adopts a self-developed integrated circuit board, which greatly improves the reliability and anti-interference of signal acquisition. The principle of the system is shown in the Fig. 6.

The dynamic signal measuring system is mainly composed of a dynamic strain gauge, a data collector and several bridge boxes, and can be matched with various strain gauge sensors (vibration pick-up, strain gauges and stress sensors, etc.). The core component of the system is the dynamic strain gauge, which has high acquisition accuracy by using a built-in high-precision amplifier, A/D converter and other preferred circuits. Vibration pick-up can be directly connected to data collector to collect acceleration, speed and other parameters. Strain gauges and stress sensors need to be connected to the bridge box and dynamic strain gauge, then to the data acquisition device to collect strain and stress parameters.

3. Function And Technical Parameters Of The System

The model test system can be used to study the stability of underground structures such as tunnels and underground caverns under static, dynamic or static-dynamic loads. The technical parameters are shown in Table 1. Its characteristics are as follows:

- (1) The model size is large, and a larger range of dynamic load disturbances can be studied.
- (2) It adopts a combined reaction frame and can be assembled freely to carry out model tests of different sizes.
- (3) It is equipped with a model moving system to facilitate the removal and retention of the model.
- (4) The front part of the model can be visualized to facilitate the application of digital image correlation (DIC) technology.

(5) It can accurately apply three-dimensional gradient static load and dynamic load with adjustable frequency, waveform and amplitude (or magnitude).

(6) It can measure displacement, stress, strain, velocity, acceleration and other important parameters during the model test with high speed and accuracy.

Table 1
Main Technical Parameters of the System

Item	Parameter	
Test bench	External size (mm)	5300×5330×3790
	Model size (mm)	3600×3600×(500 ~ 2500)
	Tunnel diameter (mm)	0 ~ 600
Static loading unit	Number of loading channels	14
	Loading range on model surface (MPa)	0 ~ 1.2
	Loading precision on model surface (MPa)	0.01
	Holding time (hours)	≥ 360
Dynamic loading unit	Loading range (kN)	0 ~ 500
	Loading precision (kN)	± 0.5
	Vibration frequency (Hz)	0.1 ~ 10
	Waveform	sine, triangle, square, random wave, etc.
Mini-grating displacement measuring system	Measuring accuracy (μm)	1
	Measuring Frequency (Hz)	1 ~ 512 k
	Measuring range (mm)	-100 ~ 100
Dynamic signal measuring system	Measuring accuracy (με)	1
	Measuring Frequency (kHz)	1.28 ~ 256
	Measuring range (με)	-5000 ~ 5000

4. Application

In order to verify the reliability and accuracy of the model test system, a static load model test and a static-dynamic load model test were carried out with a certain tunnel as the test prototype.

4.1 Test scheme

According to the similarity theory, the geometric similarity scale of the test is 1:50, the model size is 3600×3600×2500 mm after conversion, and the three-heart arch type tunnel in the model is 302 mm in height and 355 mm in width. The properties of similar materials in the model are determined according to the properties of the rock in the prototype, as shown in Table 2.

Table 2
Detailed Parameters of the Rock in Test Prototype and Model

Item	Density (kg/m ³)	Elastic modulus (MPa)	Poisson's ratio	Uniaxial compressive strength (MPa)	Cohesion (MPa)	Internal friction angle (°)
Rock	2500	14000	0.35	39	9.72	37
Similar materials in model	2400	275	0.32	0.76	0.19	36

As shown in Fig. 7(a), the static load test includes full-face excavation of the first 800 mm, step excavation of 800–1600 mm (three-step excavation) and overload test after completion of excavation. In order to describe the test process conveniently, 50 mm excavation footage is taken as one step. Then, steps 1–16 are the full-section excavation process, steps 17–34 are the step excavation process, step 35 is the overload test process, and step 36 is the model stabilization process after the overload test. The sensor layout in the static load test is shown in Fig. 7(b).

The static-motion test was carried out after the static load test. Firstly, the tunnel with stable deformation was supported by lining, and then the dynamic load was applied to the model under static state. The sensor layout in the static-dynamic test is shown in Fig. 7(c). All sensors are towards the centre of the tunnel, normal to the lining. Figure 8 shows the specific test process.

In order to further verify the accuracy of the model test results, the experimental prototype was numerically simulated using FLAC-3D, and the simulation results of the prototype were converted into the model data according to the similarity theory for comparison with the model test results.

4.2 Test results and discussion

As shown in Fig. 9, the static load test results have the same trend and final value as the numerical results. This shows that the applied static load is accurate and the collected static test data are accurate and stable.

As shown in Fig. 10, the applied dynamic load is the same as the set value, which indicates that the application of the dynamic load is accurate. Although the dynamic load changes rapidly, the trend of the displacement, strain, stress, and acceleration of the tunnel is consistent with the applied dynamic load. This shows that the collection of dynamic data is fast, which meets the test requirements. In addition, the

test results of the strain are close to the numerical results (Fig. 11), indicating that the collected dynamic data is accurate.

The above test results show that the system can accurately and steadily carry out the stability study of tunnel under static or dynamic loading conditions.

5. Conclusions

(1) A new large-scale static-dynamic model test system was developed, which consists of a static loading unit, a dynamic loading unit, a data acquisition unit and a test bench. It can be used in static, dynamic and static-dynamic tunnel stability model tests.

(2) The specially designed static loading unit can realize multi-way loading and shunt control of pressure, which can realize the precise loading of three-dimensional gradient static force. The specially designed dynamic loading reaction frame and dynamic control system can realize the accuracy and convenience of dynamic loading. The specially designed data acquisition unit can realize the diverse, precise and high frequency of dynamic disturbance information acquisition.

(3) A static model test and a static-dynamic load model test were carried out by using the system. The results of the tests are consistent with the numerical results, which proves the reliability and accuracy of the system.

Declarations

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Figures

Figure 1
Structural Diagram of the Test System

Figure 2

Test Bench: (a) Assembly sketch of test bench with different size models; (b) Visualized front reaction beam, rear reaction beam and visualized excavation window; (c) Model moving system

Figure 3

Working Principle Diagram of Static Loading Unit

Figure 4

Working Principle Diagram of Dynamic Loading Unit

Figure 5

Structural Diagram of Dynamic Loading Reaction Frame

Figure 6

Schematic Diagram of Mini-grating Displacement Measuring System

Figure 7

Test Model and Some Sensor Layouts: (a) Longitudinal diagram of tunnel model; (b) Sensor layout in static load test; (c) Sensor layout in static-dynamic load test

Figure 8

Photographs of Test Process: (a) Mining of sensor embedded space in model; (b) Embedding of Sensors in model; (c) Installation of sensors in tunnels

Figure 9

Comparisons of Displacement Between Test Results and Numerical Results in Static Load Test

Figure 10

Results of Dynamic Load Test: (a) Force-time curve of the vibration generator; (b) Vertical displacement and vertical strain at vault; (c) Vertical stresses at vault and vertical acceleration at arch bottom

Figure 11