New performance-based seismic design thought and stability evaluation of underground engineering

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Abstract

With the rapid development of the national economy and the urban modernization, the traditional intensity-based (or displacement-based) seismic design method can longer meet the demand of the seismic design of modern buildings in recent years, which is much more obvious especially for the seismic design of underground engineering. In this paper, aimed at the prominent problems for seismic safety of underground engineering at present, the prospective performance level and fortification objective based on specific structural forms, surrounding rock classifications, support types and other factors of underground engineering are determined, to ensure to fully play its functional performance and to minimize the overall loss under seismic effect that may occur in the whole life period; Based on the dynamic and static combined cycling loading method and the design strategy of the structure performance, this paper adopts the combination method of similarity physical model experiment and the numerical analog calculation to conduct dynamic damaging mechanism and performance standard design research of underground off-wall tunnel. The research results show that the dynamic and static combined cycling loading method can better reflect the generation and expansion progress of the inner micro cracks of rocks and concrete materials, thus it is an effective method to research into the damaging rules and stability of the underground off-wall tunnel; the plasticity displacement, strain and pressure stress changes of the monitoring point can better describe the damaging status of the underground projects; the increase of load magnitude can obviously result in the displacement of the monitoring point vault, which may cause the first transcending damage of the tunnel, and the cycling loading will show accumulated damage with the load magnitude positively related to the degree of accumulated damage; the strain of the monitoring point will undergo sudden changes when reaching the ultimate pressure value, while the crack width parallel to the tunnel diameter is the reference to the damaging status of the underground tunnel; the experimental and numerical simulated results coincide with each other, and can well represent the performance standard of the underground tunnel, thus providing the reference for the earthquake and explosion effect, as well as the protection a design of the underground tunnel.

Keywords: underground engineering, seismic design, seismic performance target, numerical simulation, fortification level of seismic performance, underground off-wall tunnel

1 Introduction

Underground engineering refers to engineering structure constructed in the strata below the earth's surface, namely all kinds of engineering facilities such as tunnels and caves to be dunged under the ground. These kinds of engineering structures are usually in a compressive stress-dominated semi-infinite foundation soil or rock, significantly affected and restrained by the surrounding rock or soil, being regarded as engineering with excellent seismic performance all the time. Commonly, no aseismic and shock absorption construction is designed for it. It was not until the year 1995 when the Great Hanshin Earthquake happened in Japan, which had badly damaged underground engineering such as subway stations and tunnels that broke the myth that underground engineering was safer enough to resist the earthquake for years [1-5]. Since then, the underground engineering' security has been paid attention by the society and scholars gradually. In addition, the corresponding seismic codes have been formulated according to the geological environment and earthquakes of various countries and regions [6-8].

At present, almost all nations' seismic design codes on underground engineering are designed basically by reference to the ground building structure, most of which are forecasted and evaluated according to features of the seismic peak acceleration and characteristic periods of response spectra, whose basic thoughts mainly include intensity (or strength)-based seismic design and displacement-based seismic design. The thought of intensity (or strength)-based seismic design, proposed in the early 20th century, thinks that the seismic design adopts the strength criterion, and the maximum principal stress aroused by earthquake must be less than the allowable stress [9], which requires the structure shall remain resilient or similarly resilient in the whole process of seismic action. Apparently, it is more conservative to apply in the seismic design, easily leading to bigger sectional dimension of materials and higher engineering cost; The thought of displacement-based seismic design emphasizes the displacement design and checking computations [10, 11], which, usually calculates the displacement response of the structure to ensure its reach the pre-assigned objective displacement for seismic design under the action of an earthquake with given fortification level, so as to realize the control of the structural seismic behavior. However, the seismic effect that the underground engineering may encounter great randomness in its whole life cycle, the stress state and deformation responses are also uncertain. In addition, it is hard to determine the seismic capacity itself. Meanwhile, the structure of each part of

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underground engineering tends to generate crack and extension, damage evolution, energy dissipation and other series of phenomena under seism action. Therefore, it is inappropriate to describe and judge the extremely complex state of underground engineering such as the stress and deformation and damage fracture by only using the value size of objective displacement, but it would be an effective assessment method and important quantitative index to evaluate the damage state of structures.

For all these reasons, this paper proposes a new performance-based seismic design method of underground engineering, which considers not only the stress, deformation and damage fracture for a single part in the underground structure, but also the functional performance of the whole structure under seism action; it transfers the traditional and single fortification objective based on life security to the one based on optimized decision that considers multi-factors of underground engineering, such as its purposes, geological environment, structural forms, and supporting forms and so on; in addition, it quantizes various performance indexes with the strength criterion and objective displacement as the effective assessment method and means of seismic performance to ensure and minimize the overall loss of underground engineering under seismic action in its whole life cycle.

2 Performance-based seismic design method of underground engineering

2.1 THEORY BASIS OF PERFORMANCE-BASED SEISMIC DESIGN METHOD

Because the arch structure (such as tunnels and cave depots) is the main structural form of underground engineering, the arch effect is more obvious for the underground engineering located in semi-infinite space dominated by stress, where, even a slight change of the geological environment and factors of the seismic effect will affect the stress and deformation state of the underground engineering and rock and soil bed in the adjacent area, which makes the performance judging of the underground engineering be more complex than that of ground buildings, so the seismic design method and technology lag behind that of ground buildings. At present, researchers at home and abroad solve seismic design and protection issues under the condition of specific structural forms, geological environment and seismic input mode only based on the code requirements, but without comprehensive summary and analysis of the response regularity of various operating conditions under different seismic conditions, which greatly limits the guidance to the engineering practice. Therefore, six main factors that affect the seismic performance objective and performance level of underground engineering are comprehensively analyzed in this paper, as follows:

1) Fortification of the peak acceleration.

It plays a great role in the structure of underground engineering, and refers to the seismic intensity that exceeds 10% of the probability in a region within 50 years if under earthquake action, namely the intensity corresponding to the peak acceleration stipulated in the "Ground Motion Parameter Zonation Map of China". As shown in Table 1.

TABLE 1 Relationship between seismic fortification intensity and peak acceleration

Seismic Fortification Intensity(Unit: degrees)	7	7	8	8	9
Peak Acceleration (Unit: g)	0.10	0.15	0.20	0.30	0.40

2) Structural form of underground engineering.

The underground engineering has various structural forms, usually, the three lanes, two lanes, and cave depot, separate lining, stick wall type etc.

3) Surrounding rock level.

It is divided into five levels, namely I, II, III, IV, and V.

4) Overburden depth.

It refers to the vertical distance from the top to the ground of the underground engineering, which directly affect the underground stress distribution and deformation law.

5) Fault condition.

It usually refers to the included angle of the fault cleavage plane and vertical plane.

6) Protective measure.

It refers to the applications of supporting types and damping and seismic devices.

If the above-mentioned six main factors are considered as the state variable of the performance level Y on the underground structure, the formula can be expressed as follows:

$$Y = E(E_1, E_2, E_3, E_4, E_5, E_6)\,. \tag{1}$$

That means all the factors affecting the underground engineering damage are the functionality of the performance level, and six factors comprise a sextuple pairwise orthogonal space, which also qualitatively divides the performance level into five levels (or considered to be five value segments), as shown in Table 2.

TABLE 2 The seismic performance level of underground engineering division

Types	General Description	Damage and Failure State
I	Intact structure	The whole structure is in a state of resilient basically, almost without visible cracks
II	Slightly damaged	The local structure is in the elastic-plastic state, micro cracks exist, but the structure is relatively stable on the whole
III	Heavier damaged	The structure is in the elastic-plastic state in most regions, cracks grow and accumulated damages emerge. It should be reinforced before the operation.
IV	Seriously damaged	Structures are in elastic-plastic state basically, but larger crack width appears in variable curvatures and sections, or even the concrete spalling emerges. It should be reconstructed before use
V	Nearly collapsed	The whole structure is in an unstable state, many cracks interconnect, but it hasn't collapsed yet because of the existence of the shotcreting support and other structures

Generally, most of the literature works obtain a standard basis of failure of underground engineering only by using numerical simulation, theoretical analysis and model experiment. That is to say, they just solve one or a few questions under a special condition, with a very low repetition rate of experiment. This paper firstly seeks a standard basis that can meet the performance level of underground engineering I before the seismic design, and then it changes parameter indexes of each influencing factor, to realize various state bases generated when seismic performance level I transfer into performance level V, thus forming five abstract sextuple space hyper surfaces. Owners or seismic protection designers can quickly judge the relationship between the performance level and the fortification objective of the current condition, as shown in Figure 1. If the performance level of the current condition exactly meets the seismic fortification target, the standard basis corresponding to this performance level is comparative economic and reasonable, and vice versa.

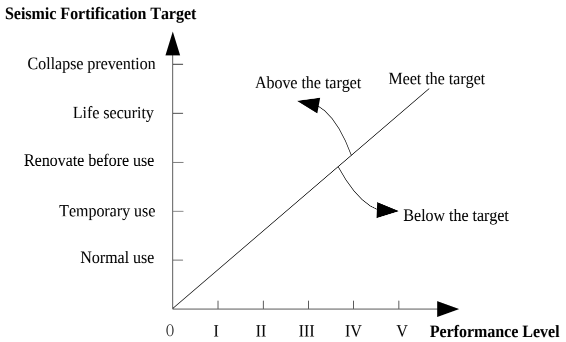


FIGURE 1 Relationship between Seismic Fortification Objective and Performance Level of Underground Engineering

2.2 PERFORMANCE- BASED SEISMIC DESIGN PROCESS

Performance-based seismic design process is usually divided into three stages as follows (Figure 2):

1) Preliminary Analysis.

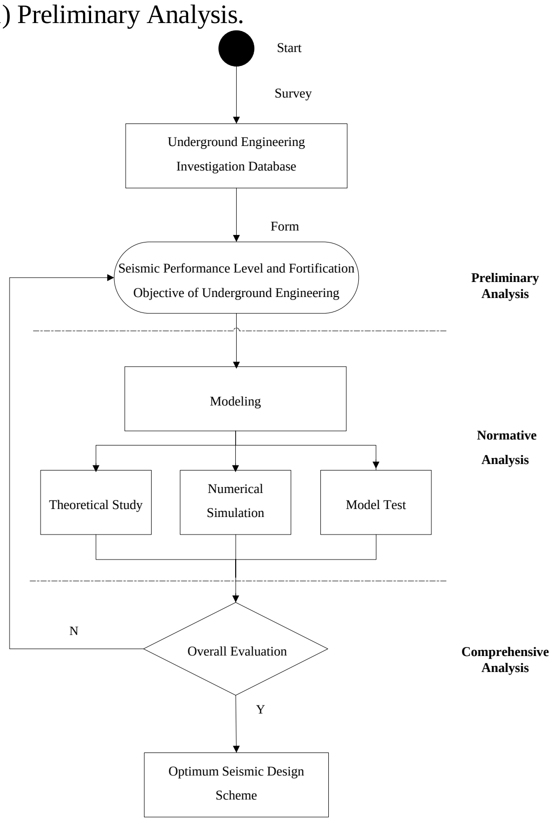


FIGURE 2 Flow Chart of Performance-based Seismic Design of Underground Engineering

Usually, the underground engineering geological investigation report includes topography and geomorphology, hydrological environment, surrounding rock classification and integrity, and intensity parameter of various surrounding rocks and so on. In addition, the previous record of seismic damage is also an important datum collected. The underground engineering fortification objective and seismic performance level can be determined according to the geological investigation, seismic damage data and local fortification intensity. For example, "when the fortification intensity is given, these underground engineering guarantees to achieve specifically seismic performance levels and fortification objectives in its whole life cycle", so that overall objectives are consistent in the whole process of seismic design.

2) Normative Analysis.

Normative analysis is a stage to seek standard bases that can meet seismic performance levels and fortification objectives by means of underground engineering design and analysis, so as to determine standard bases' specific location in these five abstract sextuple space hypersurfaces in current conditions and thus to pave the way for the comprehensive analysis. At present, the underground engineering analysis method, under the action of underground, usually includes theoretical analysis, numerical analysis and model test method, among which, the theoretical analysis focuses on the continuum model of simple construction in many supposetion conditions, but which is vulnerable to solve complicated nonlinear conditions; the numerical analysis is a method to solve approximate solutions of engineering calculating model based on the finite element, infinite element, finite difference, boundary element, discrete element and other computer methods, commonly, software such as Flac3D, Ansys, Ls-Dyna is used to realize the numerical analysis, which has advantages of easy modeling, low costs, large calculating quantity and rapidness and so on, in addition, a combination of the dynamic time-history method and response spectrum analysis has also been widely used in engineering; the model test is a method to control the boundary conditions and material properties and simulate the field geological environment by making physical model similar to the actual one, which has advantages of smaller test scale and shorter test cycle when comparing with the field test, and is also usually adopted in underground engineering structure damage, destruction and seismic protection simulation.

3) Comprehensive Analysis.

The comprehensive analysis is a stage to carry out an effective and rational judgment toward statistical results of theoretical research, numerical simulation and model test. At present, many scholars determine the damage state of underground engineering under seism action through a variety of methods and criterions. Although achieving many benefits, it has not yet formed a uniform and reasonable definition.

2.3 QUANTITATIVE DESCRIPTION METHOD OF UNDERGROUND ENGINEERING SEISMIC PERFORMANCE LEVELS

The quantization of seismic performance level of underground engineering is one of the most important links to realize the performance-based seismic design. Quantitative indexes with the intensity (or stress), displacement and damage as the design performance level are adopted in this paper to comprehensively analyze and determine its deformation and failure state.

1) Mechanical properties of surrounding rock in underground engineering and criteria.

Because the concrete and rock composing of the medium of underground engineering are brittle materials, whose tensile strength is far less than the compressive strength. Many researchers use the tensile strength of the concrete or rock as the limiting condition of its damage, namely the maximum tensile-stress criterion:

$$\sigma_1 = \sigma^t . \qquad (2)$$

In fact, the tensile strength of concrete or rock is measured under a single-shaft confining pressure-free condition, while the underground engineering is built in an environment under three principal stresses. Therefore, the existence of confining pressure exerts a tremendous influence on the damage state of concrete or rock materials, and the maximum tensile stress criterion is also not the most reasonable failure criterion people expected. In this paper, Xie Heping [12-14] obtains the rock failure criterion under the action of different sizes and directions of three main stresses through the theoretical analysis and experimental results. Obviously, the destruction of the rock unit cell is an emergent property resulting from interactions among these three principal stresses, also affected by material parameters. Many scholars and experts solve the safety coefficient of underground engineering such as tunnels and slopes [15-17] by using the strength reduction method, which integrally reduces material parameters of the whole underground engineering by a particular safety coefficients, but ignores that the stress distribution of underground structure develops regionally, while the damage happens from local part to the whole, therefore, there are a lot of defects. In this paper, the criterion of references [14], as a criterion of local or regional destructive property indexes of rock and concrete materials, can realize the control of the evolutionary process of damage and failure of the whole underground engineering structure under seism action by using the intensity parameter of rectification and iteration material unit cell when calculating the numerical simulation.

2) Deformation control index of underground engineering and surrounding rocks.

When a serious damage happens in the underground engineering in the absence of first excursion failure, the total displacement of different area is usually made of displacements generated separately by elastic deformation and plastic deformation if we assume there is no obvious opening mode crack, that is:

$$s = s^e + s^p . \qquad (3)$$

Among them, the displacement generated by the elastic deformation decreases along with the unload process, while the displacement generated by the plastic deformation is permanent. The total displacement of different area of underground engineering structure also changes along with the fluctuations of acceleration time-history curve, meanwhile, the total displacement emerges obvious changes under the action of the peak acceleration in an earthquake. The displacement generated by the plastic deformation gradually accumulates along with the duration of an earthquake, while the surrounding rock and lining structure also correspondingly cumulate the damage and ultimately leads destroyed mechanical properties. The overall safety performance of underground engineering structure can be determined based on the quantitative classification of displacement in cumulative damaged parts and the failure criterion of concrete and rock.

3 Case study

3.1 DEVICES FOR THE MODEL EXPERIMENT

This experiment adopts the side slope tunnel coupling model experiment instrument, which is jointly designed and developed by the Civil Engineering Department of Logistic Engineering University of PLA and a soil engineering instrument manufacturing plant in Shandong, China. The experiment instrument model is made up of the cuneiform side slope experiment part and the rectangular (2.0 m*0.7 m*3.0 m) tunnel experiment part. This experiment conducts loading, unloading and load holding of the model box through the microprocessor control electro-hydraulic servo tester's measurement and control system to automatic control the oil jack. At the same time, it can achieve real-time data collection, and save and update the data in the text format, which is usually of the TXT or EXCEL format (Figure 3).

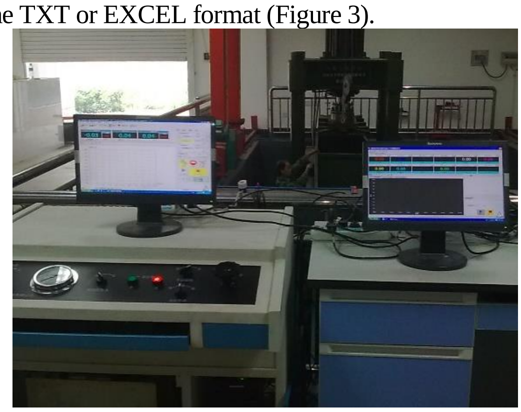


FIGURE 3 The microprocessor control electro-hydraulic servo tester's measurement and control system

FIGURE 4 The side slope tunnel coupling experiment system

3.2 SIMILARITY RELATION DESIGN

While making the similarity relation model for experiment, it should be in line with three theorems of similarity simulation, and the monodrome condition. Considering the properties of underground off-wall tunnel rock media, the model experiment should meet various indexes described in the following functions:

$$f(\gamma, c, \varphi, E, \tau, L, \mu, u_x, u_z, \sigma_x, \sigma_z, \varepsilon_x, \varepsilon_y) = 0\ , \tag{3}$$

in which gravity γ, frictional angel φ and Poisson's ratio μ are all property parameters of the materials. Since all of them belong to zero dimensions, therefore,

$$C_\gamma = C_\varphi = C_\mu = 1\,. \tag{4}$$

At the same time, in order to ensure the similarity of various strength indexes of the materials and the underground off-wall tunnel's surrounding rocks, it should meet the following criteria and requirements:

$$C_\varepsilon = C_u / C_L = 1, \tag{5}$$

$$C_\sigma = C_\tau = C_c = C_\gamma, \quad C_L = C_E C_\varepsilon = C_E\,. \tag{6}$$

According to the similarity theory, the similarity model's monodrome conditions of the underground off-wall tunnel resemble each other, and the similarity criteria (decision criteria) made up of the physical quantity of the monodrome conditions equal to each other in terms of value. However, due to the influencing factors of material making, experiment devices and techniques in the process of the experiment, it is quite difficult to make the model totally resemble the prototype. Only one or several indexes can be selected to target at solving the major problems so as to achieve the experiment goals. After analysis, the geometric conditions, critical conditions and the initial conditions of the similarity physical model are easy to obtain. Therefore, all these conditions are regarded as the basic control quantity, and set the similarity constant C_σ at 20. At the same time, the physical conditions are defined according to the parameter values in the process of mapping. It is hard to be obtained, whose similarity relation expression and similarity ratio can be indirectly gained only through the above stated similarity ratio function.

3.3 DESIGN AND MAKING OF THE SIMILARITY MODEL DESIGN

The experiment adopts steel experiment model box, whose two sides and bottom boards are both made up of 5cm steel boards, and are connected through angle iron and box iron. The underground off-wall superposition tunnel is mainly composed of painted layer of concrete, (outer lining), lining (inner arch) and the anchor-late retaining surrounding rocks' reinforced area. The specific measurements of the whole model are shown in Figure 5.

The two sides of the model are distributed with 70cm circular organic glass windows (2mm thickness), which are convenient for the researcher to observe the damaging and injury phenomena of the tunnel under the influence of the load. At the same time, the four internal side walls of the model box are all painted with Vaseline so as to fundamentally eradicate the frictional limit of the side wall. Besides, in the loading process, the loading system's bottom boards keep in full contact with the model's top to prevent the generation of bias voltage, which can influence the experiment result.

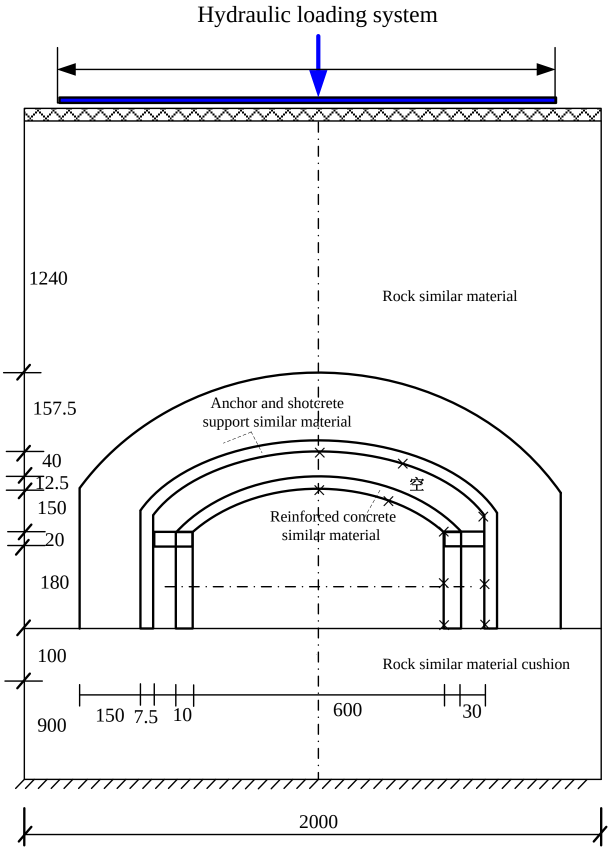


FIGURE 5 Measurement chart of the off-wall tunnel's similarity model (Unit: mm; similarity ratio: 1:20)

The similarity model in the plan imitates the tunnel body featuring the structure of "sprayed concrete-off-wall superposition." The practical working conditions are: the gross tunnel is 13.9m wide, and 8.4m high (the clear height is 7m); the outer layer of the surrounding rocks are reinforced through the anchoring-plate retaining; after the reinforcement, the strength parameters of the surrounding rocks have been improved by 5%. Considering the secondary lining only serves smooth drainage, proofing dampness and convenient repair and maintenance, its ability to shoulder and resist the pressure of the surrounding rocks is ignored temporarily. Therefore, in the process of making the assembling die, simplified treatment has been made and the die of the neck bush is not specifically made.

From the "measurement chart of the off-wall tunnel's similarity" in Figure 5, it can be seen that the similar materials of three different strength parameters should be made, namely the similar materials for the surrounding rocks, anchor-plate retaining surrounding rocks' reinforced area and the initial lining reinforced concrete. According to the similarity theory and the strength parameters of various materials, the strength parameters of the materials required to be made are shown in Table 3 (referring to the lower limit of the parameters of the three surrounding rocks as the standard).

TABLE 3 Physical-mechanical parameters of model

Composition	Type	Density (Kg/m3)	Modulus (GPa)	Poisson ratio	Cohesion (MPa)	Friction (°)
Surrounding rock	prototype	2300	6	0.3	0.7	39.00
	Model	2300	0.3	0.3	0.035	39.00
	Similarity ratio	1:1	20:1	1:1	20:1	1:1
Reinforced area	prototype	2300	6.300	0.3	0.7350	40.37
	Model	2300	0.315	0.3	0.03675	40.37
	Similarity ratio	1:1	20:1	1:1	20:1	1:1
Lining	prototype	2400	23	0.167	1.5	52.00
	Model	2400	1.15	0.167	0.075	52.00
	Similarity ratio	1:1	20:1	1:1	20:1	1:1

The materials selected for the similarity model should meet the properties of high unit weight, low strength and low elastic modulus. Moreover, in order to save the cost, all these materials should meet the requirement of repeated use as much as possible. After the model material experiment with different kinds of matching and various kinds of raw materials [8-11], it is found that the aggregate of the similar materials should include blanc fixe, silica sand and fine sand; and the cementing agent should include ethyl alcohol, Vaseline, rosin, engine oil and cement. All these materials are easy to get and make, and can be made into ones of different gravity, cohesive forces and modules of deformation through the aggregate and the cementing agent.

This paper mainly adopts the silica sand as the coarse aggregate, the blanc fixe as the fine aggregate, and cement, water and vaseline as the cementing agent. After analyzing the test result of the matching materials' strength, elastic modulus, cohesive force and other basic control variables, and rectifying them on a real-time base, this paper finally finds out that the matching ratio of 6.5:4:0.5:1:1 can reach the requirement of various parameters of the three types of surrounding rocks.

3.4 EXPERIMENT PLAN DESIGN

There are two observation windows in the whole model box, which cling to the cross section of the underground tunnel model respectively. In this way, it is easy to install the sensor and observe the damaging status. Before the experiment, three corresponding 3D numerical models are established for trial calculation. The sensor's position is rationally arranged according to the simulation result, which is shown in Figure 6:

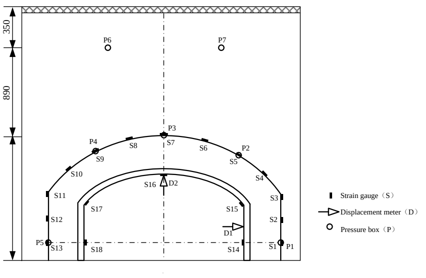


FIGURE 6 The arrangement of the monitoring point of the similarity simulation box of the underground tunnel

The major data observed and collected, and the instruments and devices adopted in this experiment include: lining inner wall displacement to be measured through the displacement meter, pressure of the surrounding rocks to be measured through the vibration-wire pressure capsule, the radial strain of lining inner wall and the surrounding rocks' reinforced area is sensed by the resistance strain gage, and conveyed through the data collection box to the computer installed with the strain measurement system, in which "S" stands for strain gage, "D" stands for displacement meter, and "P" stands for pressure box.

3.5 THE GRADED PRESSURE LOADING OF THE MODEL EXPERIMENT

Under the practical working condition, the load (such as the earthquake effect and explosion) that the underground project structure is subject to boasts large degree of randomness. Different load influences have different response models and damaging rules for the underground projects. Therefore, the model experiment loading method is a systematic and complex issue. Many articles and experiments are just analysis of the influence of the static force or dynamic force function under particular geological environment, thus are less comprehensive and lack guiding significance. Obviously, they cannot form a set of proper and universal performance design method and standard system. Through the microprocessor control electro-hydraulic servo measurement and control system, the time history curve of the graded pressures with the time. The loading process is processed according to the sequence of 1→2→4→7→10→15→20KN until it is broken. Each level of loading is cycled for five times. The low-frequency loading method can regard the loading path in the front as the foreshock, and the response under the current stress strain as the peak stress spectrum effect. In this way, the tunnel injury and damaging rules under different peak value pressures and different pressure of surrounding rocks can be simulated. At the same time, the accumulated injury effect under the dynamic and static cycling loading model can be gained. Considering the need of the follow-up loading, the pressure is transformed into the curve in which the stress strain changes with time (as shown in Figure 7, and the measurement of the loading board is 2m*0.7m):

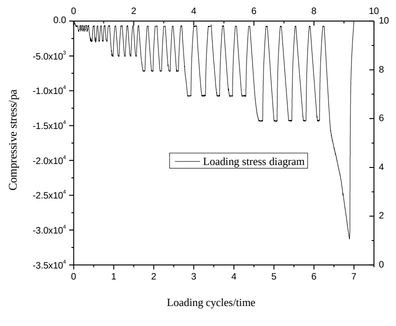


FIGURE 7 The curve chart of the graded loading stress strain changing with time

4 Results and discussion

4.1 ANALYSIS OF THE PRESSURE CHANGE RESULTS OF THE SURROUNDING ROCKS

During the process of graded loading, the pressure of the surrounding rocks undergoes no significant changes. The curve of the pressure of the surrounding rocks of the seven monitoring points is almost not involved with each other, which is shown in Figure 6. At the same time, it can be seen that the pressure of the surrounding rocks, when under the cycling loading model of the same level, shows little accumulated effect, which is almost related to the loading pressure (amplitude).

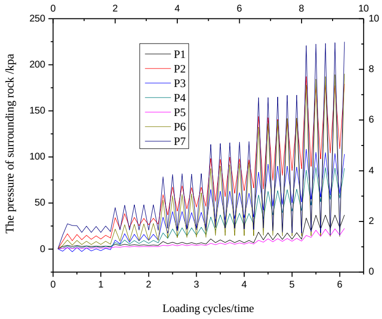


FIGURE 8 The curve chart of the pressure (kPa) of the surrounding rocks changing with time

4.2 ANALYSIS OF THE STRAIN CHANGE RESULTS

The strain monitoring points are mainly distributed in the sprayed concrete inner wall and the external side of the reinforced area of the surrounding rocks. According to the loading results, it is shown that the initial image change of the strain occurs in the third level loading, which is 10kN. The change is the most significant especially when the external side of the reinforced area of the surrounding rocks is close to the position of the vault (S6) and the sprayed concreate vault (S16). This is the crack initiation period. In the fourth level loading, which is 15kN (damage occurs in the third loading of the level), the strain gage (S16) of the sprayed concreate vault is snapped, exceeding the range limit, and the stress strain (S7) in the reinforced area of the surrounding rocks also undergoes sudden changes. This is called the crack expansion period. In the fifth level of loading, which is 20KN, there appear the per foliate cracks, and the stress strain (S7) in the reinforced area of the surrounding rocks continues to increase until it is damaged. This can be regarded as the damaging period.

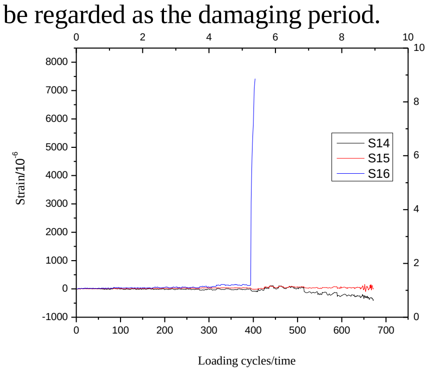


FIGURE 9 The strain change curve chart of the sprayed concrete inner wall

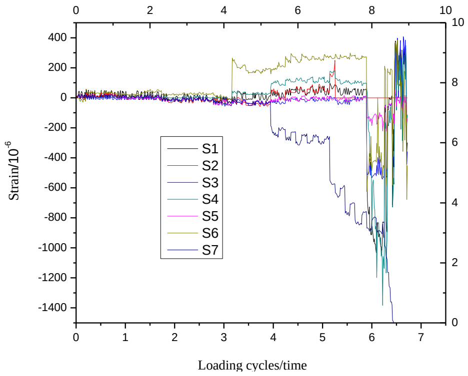


FIGURE 10 The strain change curve chart of the reinforced area of the surrounding rocks

4.3 ANALYSIS OF THE DISPLACEMENT CHANGE RESULTS

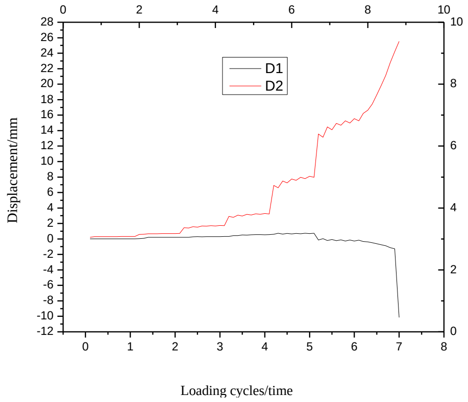


FIGURE 11 Curve chart of the sprayed concrete inner wall displacement changes

The test curve of the displacement monitoring point further verifies the monitoring result of the strain. The crack initiation period, crack period, expansion period and damaging period appear in the three levels of loading processes, 10kN, 15kN and 20kN respectively.

4.4 COMPARISON AND ANALYSIS OF THE NUMERICAL SIMULATION

The numerical simulation calculation model is built in strict accordance with the underground tunnel measurements of the model experiment. The mesh generation is shown in Figure 10. The lining and the reinforced area of the surrounding rocks are made up of the square meshes, and the triangle ones. At the same time, considering the prospective large changes occurring under the strain and deforming status near the lining, the mesh generation in this area is quite intensive. During the process of calculation, the materials of the surrounding rocks and the lining are regarded as the elastic materials, Mohr-Coulomb strength criterion is adopted and the partial damping coefficient is 0.157. In order to gain a higher degree of compatibility of the result of the numerical simulation and the model experiment, the loading curve of the model and the loading curve of the model experiment are in line with each other, and the displacement, strain and the strain marking method of the monitoring points remain consistent with each other.

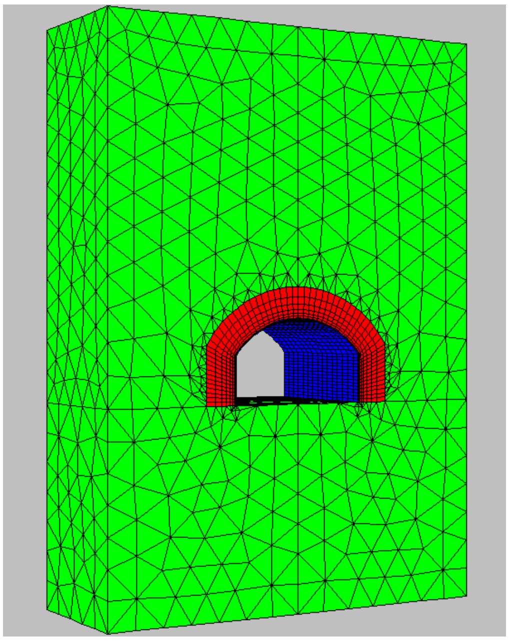


FIGURE 12 Numerical simulation mesh

The fish language embedded in FLAC3D is employed to impose the graded loading curve on the top of the model, and the strain and deforming status of various monitoring points are observed on a real-time basis. From Figure 11, it can be seen that the relative displacement of the vault and the result gained by the similarity model experiment are in line with each other, and both shows significant changes for the first time when under the loading model of 15kN. At the same time, the accumulated damage would gradually increase with the rise of the load.

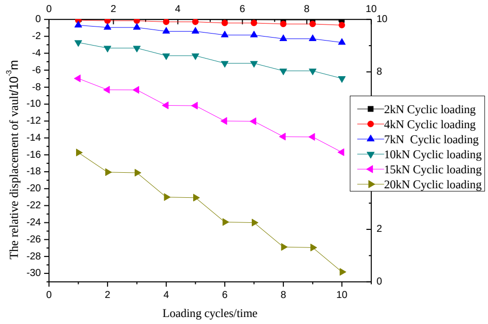
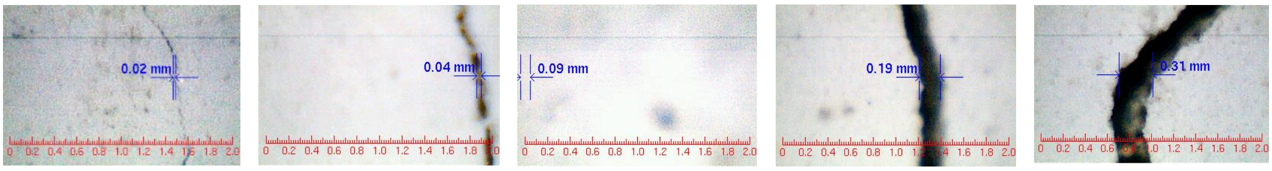


FIGURE 13 The relative displacement of various monitoring points gained after the numerical calculation

The numerical simulation result shows that the error of the displacement curve and the similarity model experiment after 15KN is comparatively large, which suggests that deformation occurs in the tunnel's vault and some part even shows damage in the loading process of above 15kN. Obviously, the simulation of FALC3D software based on the continuum theory cannot comparatively genuinely reflect the damaging status of the tunnel in the process.

4.5 PERFORMANCE QUANTITATIVE ANALYSIS

The earthquake resistant design is not only to ensure the life security within the tunnel, but also to control the damaging degree of the tunnel, making the economic losses controlled within the acceptable scope. According to the result of the experiment, the tunnel's performance stand under the function of the dynamic and static combined cycling loading can be gained, which is shown in Figure 14 and Table 4:



a) Performance level I b) Performance level II c) Performance level III d) Performance level IV e) Performance level V

FIGURE 14 The performance standard classification of the crack width and the damaging status of the tunnel's vault

TABLE 4 The comparison of the tunnel's performance standard and the model's experiment results

Category	General description	Repair measures	Pressure（KN)	Stress (Kpa/m2)	Strain	Vault displacement
I	Good performance	Normal use	1→2→4	-0.06→-0.10→-0.32	10-5 magnitude	Within 1.8 mm
II	Slight damage	Temporary use	4→7→10	-0.32→-0.50→-0.72	10-5 magnitude	Within 3.3 mm
III	Heavier damage	After the repair service	10→15	-0.72→-1.11	Arch wall strain fracture, more than 10-3 magnitude.	Within 8.1 mm
IV	Serious damage	Life safety	15→20	-1.11→-1.45	Vault and arch strain than 10-3 magnitude, over strain range	Up to 15.5 mm
V	Close to collapse	Collapse prevention	20→Destruction	-1.45→-3.16	Out of gauge	More than 25.5 mm

5 Conclusion

1) The experiment phenomena show that the dynamic and static combined cycling loading method can well reflect the generation and expansion process of the microcrack in the rocks and the concrete materials on a macro basis. This is an effective method to research into the off-wall underground tunnel. Under the condition when there are major deformation and accumulated injury statuses occurring in the tunnel, the method can comparatively genuinely reflect the damaging status of the underground tunnel.

2) The plasticity displacement, strain and stree strain changes of the underground tunnel in different monitoring points under different load conditions can well describe the damaging rules of the underground projects. The increase of

load magnitude can obviously result in the displacement of the monitoring points (vault), which may trigger the first transcending damage of the tunnel and the accumulated damage of the cycling loading. The magnitude of the load is positively related to the accumulated damage degree. The strain of the vault undergoes sudden changes in the third cycling when the load is 15KN. This suggests that the underground tunnel has undergone serious damage. The following loading process and results show that the displacement and the crack width of the vault keep increasing, but are within the controllable range.

3) In order to better control and describe the damaging rules, this paper conducts quantitative analysis of the performance index of the underground tunnel and can well match with the result of the model experiment.

4) The model experiment and the numerical simulation results show that the two coincide with each other quite well, and can well represent the performance standard of the underground tunnel, thus providing the reference for the prevention and design against and of the earthquake effect and the explosion.

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