Mechanical and Numerical Simulation on Weathered Argillaceous Siltstone under Cyclic Loading

Yang Sun¹, Chengke Zhang¹, Zhiqiang Li¹ and Junping Yu¹

¹Jiangxi Provincial Institute of Transportation Science
email: 2853@ecjtu.edu.cn
Corresponding author’s e-mail: lukeryuyang@163.com

Abstract: Secondary lining cracking always occurs in existing tunnels when the tunnel passes through the weathered argillaceous siltstone layer, which seriously affects the safety of the tunnel. In order to study the mechanical properties of weathered argillaceous siltstone and the cracking law of the secondary lining, this study analyzes the relationship of accumulative plastic strain between the dynamic stress amplitude and static deviator stress, as well as the cracking law of the secondary lining of the sample. The results show that under cyclic loading, there are obvious accumulative plastic strain in weathered argillaceous siltstone; the bearing capacity of the secondary lining structure at the biased part shows an evident increase than that of others with cracking generating faster. The research results provide a reference for the safety and operation of the tunnel that runs through the weathered argillaceous siltstone layer.

1. Introduction

Weathered argillaceous siltstone is a kind of soft rock with weak texture, thin layered structure and weathering fracture[1]. Due to its low strength and high shale content, the stability of the tunnel surrounding rock and the cracking of the secondary lining structure in the soft rock layer remain to be a major problem when the tunnel passes through the weathered siltstone layer.

In recent years, domestic and foreign researchers have conducted in-depth research on the dynamic characteristics of soft rock [2-3]. Through cyclic triaxial test of water-rich sandstone, Ding Zude [2] pointed out that the accumulative strain process of water-rich sandstone under cyclic loading shows two types: stable and destructive; Liu Jianfeng [3] et al. conducted dynamic cyclic loading tests on argillaceous siltstone and found that the loading and unloading stress-strain curves presented with a closed hysteretic loop instead of coinciding;

As the main bearing structure of tunnel in soft rock area, cracking in secondary lining structure becomes increasingly common under complex engineering geological conditions. To solve this problem, scholars at home and abroad have done a lot of research work: Singh Bhawani [4] et al. explored the relation between the lining bearing capacity and the void and insufficient thickness behind it under different load conditions through model test; Bernardino Chiaia [5] et al. established a
crack evaluation model to study the expansion law of lining cracks and safety evaluation issues;

In this paper, cyclic loading conventional triaxial tests and numerical simulation of secondary lining structure cracking of weathered argillaceous siltstone are carried out through laboratory test and numerical simulation.

2. Dynamic Deformation Test of Weathered Argillaceous Siltstone

2.1 Sample Preparation
The rock sample is chosen from the layer of weathered argillaceous siltstone in one construction site. The brownish red rock sample is in silty and layered structure with strong weathering and joint fissure. The core is fragmentary and easily to be broken by hammering. Thought core-drilling method, the core is sealed to the local geological survey institute for processing according to the method recommended by the International Society for Rock Mechanics, that is, to process it into a cylinder with a diameter of 50 mm and a height of 100 mm as shown in Fig. 1. The main physical and mechanical indexes of the soft rock measured before the test are shown in Table 1.

![Weathered Argillaceous Siltstone](image)

**Fig. 1 Weathered Argillaceous Siltstone**
**Table 1 Physical and Mechanical Indexes of Weathered Argillaceous Siltstone**

| Sample               | Natural density ρ (g/cm³) | Internal friction angle φ(°) | Cohesion c(kPa) | deformation modulus E( MPa) | Permeability coefficient k(m/d) | Poisson’s ratio μ | characteristic value of subgrade bearing capacity f_0(kPa) |
|----------------------|---------------------------|------------------------------|-----------------|-----------------------------|-------------------------------|------------------|--------------------------|
| Weathered Argillaceous Siltstone | 2.02                       | 25                           | 40              | 80                          | 0.8                           | 0.32             | 450                       |

2.2 Test Equipment and Test Scheme
The research is aimed to the weathered argillaceous siltstone by using ZTRE-210 microcomputer-controlled rock triaxial test system. The test machine has a maximum axial load of 2000 kN, a confining pressure of 100 MPa, and a vibration frequency of up to 5Hz. The vibration waveforms include sine wave, cosine wave, triangle wave, square wave, oblique wave, etc., meeting all range and accuracy requirements of this test.

In the test, the deformation control loading mode is introduced and the cyclic load is simulated by sine wave, and the influence of dynamic stress amplitude and static deviator stress on the deformation characteristics of weathered argillaceous siltstone are comprehensively considered. The confining pressure was stabilized to 300 kPa, and the dynamic stress amplitude and static deviator stress are determined according to the research of Zhao Dan et al. [6]. Table 2 shows the test loading operation
Before the test, the rock sample with large dispersion is removed by measuring the wave velocity. After fixing the rock between the two pads and heat shrinkable tube, the pressurization system is connected to add confining pressure to the set value, and then, MTS is loaded to the loading plate contacts with the rock sample. Finally, the sine wave cyclic loading is applied, and the cycle loading times are set as 5000 times.

### Table 2 Test Loading Operation Model

| Operation model | Dynamic stress amplitude (kPa) | Static deviator stress (kPa) | Vibration frequency (Hz) | Confining pressure (kPa) |
|-----------------|-------------------------------|----------------------------|--------------------------|--------------------------|
| 1               | 30, 60, 90, 120, 180          | 120                        | 1                        | 300                      |
| 2               | 60                            | 0, 60, 120, 180, 240        | 1                        | 300                      |

2.3 Analysis on the Test of Dynamic Deformation Characteristics of Weathered Argillaceous Siltstone

#### 2.3.1 Analysis on the Influence of Dynamic Stress Amplitude

Operation model 1: Under the fixed static deviator stress of 120 kPa, confining pressure of 300 kPa and loading frequency of 1Hz, five models of dynamic stress amplitude in 30 kPa, 60 kPa, 90 kPa, 120 kPa, 180 kPa are proposed to conduct triaxial tests for dynamic triaxial test to analyze the development law of cumulative plastic deformation of weathered soft rock. Figure 2 shows the relation between dynamic strain changes in different dynamic stress amplitudes.

![Figure 2 Dynamic Strain Cyclic Relation Curve in the Dynamic Stress Amplitude](image)

Figure 2 Dynamic Strain Cyclic Relation Curve in the Dynamic Stress Amplitude

Figure 2 shows:

1. Under cyclic loading, there are obvious accumulative plastic strain in weathered argillaceous siltstone. The dynamic strain of rock sample increases as the dynamic stress amplitude increases. All five curves in Fig. 2 are stability curve in similar deformation laws, that is, the deformation of rock sample accelerates at the initial stage of loading, and tends to be stable when the times of cycles reaches about 800.

2. Compared with the existing research about soft rock, Ding Zude [2] proposed that common rock generally presents two deformation curves: deformation stability type and deformation destruction type. The dynamic strain curves of weathered argillaceous siltstone in this group of test data are stable, which may because that the dynamic stress fails to reach the critical value due to a small amplitude selected.

#### 2.3.2 Analysis on the Influence of Static Deviator Stress

Operation model 2: Under the fixed dynamic stress amplitude of 60 kPa, confining pressure of 300
kPa and loading frequency of 1Hz, five models of static deviator stress of 0 kPa, 60 kPa, 120 kPa, 180 kPa and 240 kPa are proposed to conduct triaxial tests to analyze the influence of static deviator stress on cumulative plastic deformation of weathered soft rock. Fig. 3 shows the dynamic strain relation in different static deviator stress.

![Relation Curve of Dynamic Strain Cycle Times](image)

Figure 3 shows:

1. When the dynamic stress amplitude is constant, the increase of static deviator stress will lead to the increase of dynamic strain and growth rate, especially when the static deviator stress is greater than 180 kPa, the growth rate is particularly obvious. The cycle times required for the cumulative deformation for stability is also increasing with the increase of static deviator stress.

2. When the static deviator stress is 0 kPa, the dynamic strain of 5000 times is 0.0517%; when the static deviator stress is 240 kPa, the dynamic strain of 5000 times is 0.4428, 8.56 times of the former. It is found that the increase of static deviatoric stress leads to the expansion of internal cracks in weathered argillaceous siltstone, and accordingly, the dynamic strength of rock sample decreases.

3. Numerical Simulation of Secondary Lining Cracking of Tunnel

3.1 Calculation Model of Secondary Lining Structure
In this paper, the author uses "loading structure" model to analyze the second lining steel-concrete structure as a whole without considering the construction joints. The data of external load of the secondary lining structure is from the field data of the tunnel vault and hence with bias section. In order to analyze the influence of basis caused by anisotropic characteristics of weathered argillaceous siltstone on secondary lining structure, three operation models are set up as shown in Table 3.

| Operation Model | Vault(Mpa) | Left Hance(Mpa) | Right Hance(Mpa) | Left-Side Wall(Mpa) | Right-Side Wall(Mpa) |
|-----------------|------------|-----------------|------------------|--------------------|---------------------|
| Operation Model1 | 0.586      | 0.523           | 0.537            | 0.438              | 0.505               |
| Operation Model2 | 0.778      | 0.435           | 0.426            | 0.314              | 0.327               |
| Operation Model3 | 0.417      | 0.778           | 0.327            | 0.451              | 0.030               |

Notes: Operation Model 1: no bias; Operation Model 2: bias in vault; Operation Model 1: bias in Hance;
3.2 Secondary Lining Structure Model

According to the basic assumptions and material parameters above, the numerical calculation model of secondary lining structures are established as shown in Fig. 4 and Fig. 5.

![Fig. 4 Finite Element Model of Secondary Lining Steel-Concrete Structure](image1)

![Figure.5 Reinforcement Cage Unit](image2)

3.3 Analysis on Cracking Characteristics of Secondary Lining Structure

Through the numerical calculation of the above three operation model, the crack distribution of the secondary lining structure in different bias is obtained. Under no bias, the secondary lining structure in operation model 1 has less cracks under uniformly distributed load, which only appear in symmetry in the inner side of the vault, the outer side of the two hance and the inner side of the two arch feet.

In operation model 2 with basis in vault, the inner side of the vault with secondary lining structure has the most cracks, and some cracks also appear in the outer side of the two hance, the inner side of the two arch feet. In operation model 3, when there is bias in the left hance of secondary lining structure, the inner side of both left and right hance have the most cracks, some cracks also emerge in the outer side of the left arch feet and inner side of the right arch.

Through the analysis of the crack location of the secondary lining structure under different bias pressure in three operation models, it is found that the bias pressure has a great influence on the crack distribution and crack expansion of the secondary lining structure. Bias effect causes bending moment of the secondary lining structure, and the cracks will first occur on the lining inner surface corresponding to bias section, and gradually expand to other parts.

4. Conclusion:

(1) The accumulative plastic strain increases with the times of dynamic stress cycles or static deviator stress. Similar to the loading method of dynamic stress amplitude, the plastic strain accumulates fastest in the previous period, when the times of loadings is less. With the increasing of cycle times, the plastic strain accumulates slower. The increase of the static deviator stress contributes to the expansion of internal fissures in the weathered argillaceous siltstone, and the dynamic strength of the rock sample decreases accordingly;

(2) Through the triaxial cyclic loading test, it is found that the dynamic stress amplitude and static deviator stress have great influence on the strength and stability of weathered argillaceous siltstone. During the tunnel construction, the construction vehicles and machinery conduct cyclic loading and unloading actions to the bottom of the tunnel bottom. The stress redistribution in the surrounding rock results to the pressure imbalance of tunnel surrounding rock and change in the load of the secondary
lining structure. This is how the damage happens.

(3) According to the anisotropic characteristics of weathered argillaceous siltstone, numerical simulation analysis is carried out for tunnel secondary lining structure in three operation models, namely no bias, bias in vault and bias in hance. Through the analysis of crack distribution and expansion of secondary lining structure in various operation models, it is found that without bias, the secondary lining structure has fewer cracks in overall. The cracks of the secondary lining structure will increase obviously under bias, especially in the part where the bias occurs, the crack expansion is particularly significant. It proves that the anisotropy of weathered argillaceous siltstone is an important factor contributing to the cracks in secondary lining fractures.

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