Experimental study on dynamic stress dynamic strain relationship and dynamic modulus of reinforced expansive soil

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Abstract. Dynamic triaxial tests are carried out on saturated expansive soil of Qinchong Road, Guangxi at different compaction degrees, numbers of reinforced layers, confining pressure, dynamic stress dynamic strain relationship, and dynamic modulus attenuation law under frequency combination to study the dynamic characteristics of reinforced saturated expansive soil under different influencing factors. Results show that the dynamic constitutive relationship of the saturated expansive soil when the loaded waveform is a half-sine wave conforms to the R. L. Kondner hyperbolic model; the dynamic elastic modulus decreases with the increase of dynamic strain, and the relevant fitting parameters are given. A dynamic elastic modulus attenuation model considering different degrees of compaction, numbers of reinforced layers, confining pressure, and frequency is proposed through regression analysis of the test results.

1. Introduction
Expansive soil is mainly a highly plastic clay composed of strong hydrophilic minerals. It is widely distributed worldwide and has strong swelling, shrinking characteristics, and fissures. It brings great harm to engineering construction, heavy losses, and increased difficulty in prevention and control. More expansive soil belts will inevitably be crossed with the rapid development of expressways and high-speed railways. Vehicle loads and driving speeds continue to increase, and the requirements for subgrade bearing capacity are becoming higher. For the traffic roadbed built in the expansive soil area, serious roadbed settlement, slope cracking and deformation, and other geological disasters often occur under the multiple influences of long-term traffic cycle load and geographic climate environment [1-2], which seriously affects traffic-driving safety and causes huge economic losses. Therefore, the experimental research on the dynamic characteristics of expansive soil has great engineering practical significance.

At present, most scholars simulate the influence of cyclic loading on the dynamic characteristics of soil based on indoor dynamic triaxial tests [3-8]. Cyclic loads used for simulation mainly include sine waves, half-sine waves, triangular waves, and irregular waves. Most of them are undrained triaxial tests. The frequency range of loading is between 0.1 and 10 Hz. Load application forms are mainly continuous loading and step loading [9-10].

Although many scholars have carried out much research work on the dynamic characteristics of soil, the dynamic characteristics of special soils, especially expansive soils, are extremely
complicated. At present, dynamic triaxial tests under half-sine wave cyclic loading are carried out on reinforced saturated expansive soils. Experiments are relatively few, and the research is not thorough enough. The engineering characteristics of expansive soil in various regions are quite different, because expansive soil has evident regional characteristics and is affected by various aspects such as climate environment and physical and chemical composition. Thus, this paper selects the expansive soil of Guangxi Qin Chong expressway to conduct indoor dynamic triaxial test, analyzes the dynamic characteristics of reinforced saturated expansive soil, and provides references for engineering design and research in expansive soil areas.

2. Material and Methods

2.1. Testing soil sample

The expansive soil for the test is taken from K59+300, Qin Chong Road, Guangxi at a depth of 1.5–2.0 m. It is striped (gray, purple, and yellow stripes) weathered mudstone, which is hard plastic to hard. The maximum dry density of expansive soil is 1.84 g/cm³, the optimal water content is 16.89%, and the free expansion rate is 53.5%. According to the current “Code for Highway Engineering Geological Survey” (JTG/C 20—2011) and “Code for Railway Engineering Geological Survey” (TB 10012—2019), it can be categorized as weakly expansive soil, and its basic physical properties are shown in Table 1.

| Natural moisture content (%) | Liquid limit (%) | Plastic limit (%) | Plasticity index | Montmorillonite content (%) | Specific surface area (m²/g) | Free expansion rate (%) |
|-----------------------------|------------------|-------------------|-----------------|----------------------------|-----------------------------|------------------------|
| 24.75                       | 48.86            | 24.64             | 24.22           | 15.05                      | 135.86                      | 53.5                   |

In the experiment, all cylindrical remolded soil samples with diameter D=50 mm and height H=100 mm are selected. The retrieved soil samples are air-dried naturally, and the air-dried moisture content is determined to be 2.89%. They are crushed through a 2 mm sieve with a rubber hammer and configured into wet soil at a moisture content of 16.89%. The stuffed material is divided into four layers by static pressure after 24 h. The required degree of compaction for each sample is determined by the calculation of the maximum dry density of 1.84 g/cm³. Sample preparation is carried out in strict accordance with the current “Highway Geotechnical Test Regulations” (JTGE40-2007).

2.2. Testing plan

The test instrument adopts the British GDS (Geotechnical Digital System) advanced dynamic three-axis testing system, as shown in Figure 1. It is composed of computer data acquisition system, back pressure, confining pressure controller, test host, and pressure chamber. The frequency can be set in the range of 0–5 Hz, and the maximum can be with an axial load of 10 kN. The confining pressure and pore water pressure can be monitored in real time, and saturation detection can be performed to meet the requirements of normal tests.
Considering that sine waves and half-sine waves are generally used to simulate cyclic loads during the test, the cyclic stress ratio ($\sigma_d/2\sigma_3$, $\sigma_d$ is the axial dynamic stress, and $\sigma_3$ is the confining pressure) is between 0.1 and 6.0 [11-12]. After comprehensive analysis, this half-sine wave is selected for this testing, and the cyclic stress ratio is 0.1–0.6. A graded cyclic loading test is carried out for each sample, and each grade is loaded for 10 times. The test confining pressures are 50, 100, and 150 kPa. Combined with the current “Technical Specification for Highway Subgrade Construction” (JTG F10-2019), the subgrade compaction standard generally requires more than 90%, and the compaction of the sample is controlled at 90%, 92%, and 94%. The load is borne by the subgrade, and the frequency is related to the speed of the vehicle. The vehicle load frequency is generally about 1 Hz, and the test loading frequencies are 1, 1.5, and 2 Hz. Glass fiber window screening that is used to simulate the geogrid is reinforced, and the mass per unit area is about 120 g/m² due to the small sample size and to reduce the size effect of the reinforced material. According to the current “Highway Engineering Geosynthetics Test Regulations” (JTG E50—2006), the maximum tensile force under the wide strip tensile test is about 2.03 kN. The elongation rate is 10.7%, and it is divided into one and two layers of horizontal reinforcement. The reinforcement materials and schematic diagrams are shown in Figure 2 and 3. Figure 4 is a comparison diagram before and after the failure of the two layers of reinforcement of the sample, showing that the middle part of the sample is damaged.

![Figure 2. Reinforced material.](image)

![Figure 3. Reinforcement diagram.](image)

![Figure 4. Before and after sample failure.](image)

### 3. Results

#### 3.1. Dynamic stress dynamic strain curve

Figure 5 shows the dynamic stress and dynamic strain relationship curve, and Table 2 shows the fitting parameter table of the dynamic stress and dynamic strain relationship.

| Numbering | $a \times 10^{-3}$ | $b \times 10^{+1}$ | $R^2$          |
|-----------|--------------------|--------------------|----------------|
| 1         | 2.2                | 23.8               | 0.9989         |
| 2         | 2.0                | 19.0               | 0.9994         |
| 3         | 1.9                | 18.5               | 0.9999         |
| 4         | 2.0                | 19.5               | 0.9995         |
| 5         | 1.9                | 18.0               | 0.9998         |
| 6         | 1.8                | 18.0               | 0.9995         |
| 7         | 2.1                | 19.5               | 0.9993         |
| 8         | 1.7                | 18.6               | 0.9992         |
| 9         | 1.5                | 15.8               | 0.9996         |

Figure 5 shows that the dynamic stress dynamic strain relationship of saturated expansive soil under different factor levels shows a nonlinear growth and strain hardening characteristics. Hyperbolic fitting is used to compare and analyze each test point. In Figure 5, $a$ and $b$ are fitting parameters, and determination coefficient $R^2$ is above 0.998 (see Table 2), indicating that the dynamic stress and strain shape of the saturated expansive soil on Qin Chong Road still conforms to the R. L. Kondner hyperbolic model, the parameter range is between $1.5 \times 10^{-3}$–$2.2 \times 10^{-3}$, and
the parameter range is between $15.8 \times 10^{-3} - 23.8 \times 10^{-3}$. Parameter $b$ is approximately 10 times parameter $a$.

3.2. Establishment of dynamic elastic modulus attenuation model

According to the definition of dynamic elastic modulus,

$$E_d = \frac{\sigma_d}{\varepsilon_d} \quad (1)$$

where $\sigma_d$ and $\varepsilon_d$ are the corresponding dynamic stress and dynamic strain under various loads, respectively. The relationship curve between the dynamic elastic modulus and dynamic strain of saturated expansive soil under each factor level is shown in Figure 6, where the dynamic elastic modulus of saturated expansive soil decreases non-linearly with the increase of dynamic strain under different factor level combinations.

![Figure 6. Dynamic resilience modulus dynamic strain relationship curve.](image)

Figure 6. Dynamic resilience modulus dynamic strain relationship curve.

Figure 5 shows that the relationship between saturated expansive soil $\sigma_d$ and $\varepsilon_d$ presents a hyperbolic shape:

$$E_d = \frac{\sigma_d}{a + b \varepsilon_d} \quad (2)$$

Equation (3) can be obtained by combining Equation (1) and (2). $1/E_d$ and $\varepsilon_d$ are linearly related, and Equation (3) is used for linear fitting of each test result. The fitting curve is shown in Figure 7, and the fitting results are listed in Table 3, (where $a$ and $b$ are fitting parameters, and $R^2$ is the coefficient of determination). Figure 7 and Table 3 show that most of the test points are on the fitted curve, and $R^2$ is greater than 0.992, indicating that the dynamic constitutive relationship of the saturated expansive soil on Qin Chong Road under half-sine wave simulated cyclic loading can be described by the R. L. Kondner model, which is consistent with the analysis result in Figure 5.

$$\frac{1}{E_d} = a + b \varepsilon_d \quad (3)$$

![Figure 7. Fitting of dynamic elastic modulus dynamic strain relationship.](image)

Combining the above test data and performing regression analysis, a dynamic elastic modulus

| Numbering | $a \times 10^{-3}$ | $b \times 10^{-3}$ | $R^2$ |
|-----------|-------------------|-------------------|-------|
| 1         | 22.4              | 236.8             | 0.9975|
| 2         | 20.7              | 188.8             | 0.9984|
| 3         | 19.1              | 184.5             | 0.9997|
| 4         | 20.0              | 193.3             | 0.9979|
| 5         | 19.3              | 179.3             | 0.9994|
| 6         | 18.0              | 178.1             | 0.9976|
| 7         | 21.6              | 189.7             | 0.9930|
| 8         | 17.0              | 181.2             | 0.9925|
| 9         | 15.5              | 156.5             | 0.9980|
attenuation model considering the relationship between different confining pressure, compaction, numbers of stiffened layers, and frequencies with dynamic strain is proposed:

\[ E_d = \frac{0.081\sigma_{3c} + 2.624p - 1.42n + 0.069f - 195.72}{1 + 9.54E_d} \]  

(4)

Where \( \sigma_{3c} \) is the confining pressure (kPa), \( p \) is the degree of compaction (%), \( n \) is the number of stiffened layers, and \( f \) is the frequency (Hz). Figure 8 compares the test results and the model curve under different confining pressure, degrees of compaction, numbers of reinforced layers, and frequencies. Figure 8 shows that the attenuation model curve agrees with the test results, which verifies the correctness of the dynamic elastic modulus attenuation model curve.

4. Conclusions

Through dynamic triaxial indoor test and fitting analysis, the following conclusions are mainly obtained:

1) The dynamic constitutive relationship of the reinforced saturated expansive soil on Qin Chong Road conforms to the R. L. Kondner hyperbolic model. Under a small dynamic stress loading, the sample approximately exhibits elastic characteristics. When the dynamic stress gradually increases, the strain hardening characteristics are gradually evident, the dynamic elastic modulus and the amount decrease nonlinearly with the increase of dynamic strain, and the softening rate of soil stiffness first increases and then decreases.

2) A model of dynamic elastic modulus attenuation considering different confining pressure, degrees of compaction, several reinforced layers, and frequencies is proposed. The accuracy of the attenuation model is verified through comparative analysis with test data, which can be used for dynamic expansion of expansive soil. The elastic modulus research provides reference.

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