Experimental study on dynamic shear modulus and damping ratio of remolded loess

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Abstract. Dynamic shear modulus and damping ratio are two important parameters to characterize the dynamic characteristics of soils. In this paper, the influence of dry density and consolidation pressure on dynamic shear modulus and damping ratio of remolded Guyuan loess is studied by resonant column tester. The results show that the maximum damping ratio decreases with the increase of dry density and consolidation confining pressure. Under the same dry density condition, the dynamic shear modulus ratio of loess increases with the increase of confining pressure; the damping ratio decreases with the increase of confining pressure; under the same confining pressure, the dynamic shear modulus ratio of loess increases with the increase of dry density, and the damping ratio decreases with the increase of dry density; the research results can provide basic information for site seismic response analysis and engineering construction in this area.

1. Introduction

Loess is widely distributed in the northwest loess plateau. The global loess area is about $13 \times 10^6 \text{km}^2$, accounting for 9.8% of the earth's land area[1]. Guyuan in the northwest region of the Loess Plateau, this area has complex topography and frequent earthquakes. Because it is located at the junction of the arc fault zone of the Qinghai-Tibet Plateau and the ring structure of South Ordos, this particular geological structure environment makes this area a seismic-prone area in China. Especially the Haiyuan Earthquake in 1920, which was the highest intensity earthquake in the loess area recorded in China, caused a large area of loess earthquake subsidence landslide and other serious disasters and loss of life and property in Xihaihu area. Guyuan loess stratum has potential risk of collapsibility, earthquake subsidence, landslide and liquefaction[2], so it is necessary to study the Loess in this area. Guyuan loess is mostly Unsaturated Silt with high silt content and low plasticity index. The microstructure of loess is characterized by macropore and weak cementation. The elastic-plastic deformation characteristics of loess in different regions are studied by means of the microstructure of Loess (Deng Jin, 2013) [3].

The resonant column test has the advantages of reliable test results, can be carried out under medium and small strains ($10^{-6}$–$10^{-2}$), and stable stress conditions. Huang Bo et al. [4] studied the dynamic characteristics of saturated silt and silt, and obtained the difference of shear wave velocity between natural soil and indoor samples. Huang Zhiquan et al. [5] Experimental studied on dynamic
parameters of unsaturated loess with different fines content by resonance column test. The influence of experimental errors of dynamic shear modulus ratio and damping ratio on the results of ground motion calculation (Li Xiaofei, et al) [6]. Xu Jie et al. [7] carried out suction-controlled resonant column tests and mercury injection tests on compacted unsaturated loess specimens, and studied the relationship between initial shear modulus and pore size distribution of unsaturated loess. Study on the shear modulus and damping ratio of silty clay by soil sample depth (Tan Huiming, 2015)[8].

The dynamic shear modulus and damping ratio obtained by resonance column test are important parameters of soil dynamic characteristics [9]. They are indispensable dynamic parameters in seismic response analysis of soil and foundation, and also indispensable parameters in seismic zoning analysis. It is important to study the dynamic characteristic parameters of loess for preventing and controlling engineering disasters. In the past, the influence factors of confining pressure and dry density on modulus-damping ratio of loess in $10^{-4} \sim 10^{-2}$ strain range were seldom studied. In this paper, Guyuan loess is taken as the research object, and the dynamic shear modulus and damping ratio of remolded loess are taken as dynamic indexes by resonance column test under medium and small strain amplitude. The regularity of the dynamic shear modulus and damping ratio of remolded loess is explored and analyzed, which provides basic data for site seismic response analysis and engineering investigation in this area.

2. Microstructure analysis

The results of SEM scanning test of loess samples in Guyuan area of Ningxia are shown in Fig. 1. The microcosmic parameters obtained by PCAS processing are shown in Table 1. The results of microscopic particles with different multiples are shown in Fig. 2.

![Figure 1. Micro structure of Guyuan Loess at Different Amplification Ratios](image)

| Sampling locations | Magnification | fractal dimension | Probability Entropy | Average form factor |
|-------------------|---------------|-------------------|---------------------|--------------------|
| Guyuan, Ningxia   | 500           | 0.8336            | 0.8391              | 0.5404             |
|                   | 1000          | 0.9401            | 0.796               | 0.5165             |
|                   | 1500          | 0.9341            | 0.8715              | 0.5564             |
Figure 2. Microscopic particle results with different multiples

1) Fractal dimension
The particle morphology of loess samples has fractal characteristics. The relationship between particle area and perimeter [11] in the image is as follows:

$$\log P = \frac{D}{2} \log S + C$$

(1)

$D$ is the fractal dimension corresponding to loess particle morphology; $P$, $S$ are the equivalent perimeter and area of any particle in the image. $C$ is constant. Fractal dimension usually reflects the orientation of Loess microstructure. The smaller the value of fractal dimension, the better the orientation; the larger the value, the worse the orientation. The fractal dimension of Guyuan loess varies from 0.8336 to 0.9401 under different magnification.

2) Probability Entropy

$$H = -\sum_{i=1}^{n} p_i \log(p_i)$$

(2)

Whereas $p_i$ is the percentage of particles in a specific range of directions. $n=18$. That is to say, the direction interval of $0^\circ$-$180^\circ$ is divided into 18 parts. Its value varies between 0 and 1. It is used to describe the directivity of particle system. When probability entropy equals 0, it indicates that all particles are in the same direction. When probability entropy equals 1, the particles are evenly distributed in all directions. With the increase of probability entropy, the orientation of particles decreases and the direction of particles tends to be random. The probability entropy of Guyuan loess varies from 0.796 to 0.8715 under different magnification.

3) Average form factor

The complexity of block shape is represented by the area and perimeter of the block.

$$F = 4 \times \pi \times S / C^2$$

(3)

Average form factor represent the boundary roundness of blocks, whose values range from 0 to 1, and for the circle and square, their shape coefficients are 1 and 0.785. The bigger the shape coefficient is, the smoother the particle shape is, and vice versa, the longer the particle shape is. The average form factor of Guyuan loess varies from 0.5165 to 0.5564 under different magnification.

3. Introduction to the experiment

3.1 Introduction of Soil Samples

Soil samples were collected from Guyuan, Ningxia, and the particle composition was mainly silt. The Guyuan loess was dried for 12 hours with DHG-9070A blast dryer, and the controlled temperature was 105-110 C. Then the soil sample is crushed with a crusher and passed through a 0.5mm sieve. The soil under the sieve is taken as the test sample. The physical properties and schemes of soil samples are shown in Tables 2 and 3.
Table 2. Physical properties of test loess and numbers of loess samples

| Sampling locations | water content /% | dry bulk density (kN/m³) | void ratio | Plasticity index | Clay particle /% | Silt /% | sand /% |
|--------------------|------------------|---------------------------|------------|------------------|------------------|---------|---------|
| Guyuan, Ningxia    | 12 ~ 15          | 15.5 ~ 18.4               | 0.48 ~ 0.74| 6 ~ 10           | 14               | 55      | 36      |

Table 3. Torsional resonant column testing program

| Test condition | Sample number | water content (%) | dry density (g/cm³) | Consolidation ratio | void ratio | Consolidation pressure (kPa) |
|---------------|---------------|-------------------|--------------------|---------------------|------------|----------------------------|
| Condition 1   | GY01-1        | 1.55              | 1.0                | 0.74                | 100        | 200                         |
|               | GY01-2        | 15                | 1.68               | 1.0                 | 0.61       | 200                         |
|               | GY01-3        | 1.72              | 1.0                | 0.57                | 100        | 200                         |
|               | GY02-1        | 1.84              | 1.0                | 0.48                | 200        | 400                         |
| Condition 2   | GY02-2        | 14                | 1.63               | 1.0                 | 0.66       | 200                         |
|               | GY02-3        | 1.61              | 1.0                | 0.68                | 100        | 200                         |
|               | GY03-1        | 1.59              | 1.0                | 0.70                | 200        | 400                         |
| Condition 3   | GY03-2        | 12                | 1.66               | 1.0                 | 0.63       | 200                         |
|               | GY03-3        | 1.73              | 1.0                | 0.56                | 200        | 400                         |

4. Analysis of test results

In this paper, the dynamic shear modulus and damping ratio of soil samples under resonance are calculated according to the following formula:

\[ G_d = \left( \frac{2\pi f}{h} \right)^2 \rho_o \left( \frac{h_c}{\beta_s} \right) \]  (4)

Among them, \( G_d \) - dynamic shear modulus (kPa); \( f \) - The measured resonance frequency (Hz); \( h_c \) - The height of the specimen after consolidation (cm); \( \rho_o \) - Sample density (g/cm³); \( \beta_s \) - Quantitative Frequency Factor.

For the dynamic stress-strain relationship of soil, it can be inferred that:

\[ \frac{1}{G_d} = \frac{r_d}{\gamma} = a + by \]  (5)
In the formula, \( \tau_d \) is dynamic shear stress, \( \gamma \) is dynamic shear strain, \( G_j \) is dynamic shear modulus corresponding to \( \gamma \), \( a, b \) test parameters are determined by test data. \( G_{d,\text{max}} = \frac{1}{a} \) is the maximum dynamic shear modulus.

The damping ratio of soil sample can be expressed by empirical formula as follows:

\[
\lambda = \lambda_{\text{max}} (1 - \frac{G_d}{G_{d,\text{max}}})^m
\]

(6)

Formula \( \lambda_{\text{max}} \) is the maximum damping ratio and \( m \) is the test parameter. It is determined by the test data.

According to the maximum dynamic shear strain, resonance frequency, dynamic shear modulus and damping ratio measured by resonance column test, the maximum dynamic shear modulus and damping ratio can be obtained by regression calculation with least square method. The relationship curve of dynamic shear modulus ratio and damping ratio with shear strain can be obtained by fitting. The results are shown in figs. 4 and 5.

4.1 Maximum Damping Ratio

The relationship between the maximum damping ratio and consolidation confining pressure at the same moisture content and different dry densities is plotted. The results are shown in Fig. 3. From the curve, At the same water content, the maximum damping ratio decreases with the increase of confining pressure, and at the same confining pressure amplitude, the damping ratio decreases with the increase of dry density.

4.2 \( \frac{G_d}{G_{d,\text{max}}} \sim \gamma \) and \( \lambda \sim \gamma \) curves under different confining pressures and dry density

The experimental results of dynamic shear modulus ratio and damping ratio are shown in Fig. 4. The curves of dynamic shear modulus, damping ratio and shear strain of Guyuan loess under different confining pressures and dry densities are compared and analyzed. The results show that the dynamic shear modulus ratio decreases with the increase of shear strain and the damping ratio increases with the increase of shear strain while the dry density remains unchanged, and the dynamic shear modulus ratio of loess increases with the increase of shear strain. The damping ratio decreases with the increase of confining pressure. When consolidation pressure is constant, the dynamic shear modulus ratio of loess increases with the increase of dry density and the damping ratio decreases with the increase of dry density at the same shear strain amplitude.
(1) $\rho_d = 1.55 \text{g/cm}^3$
(2) $\rho_d = 1.68 \text{g/cm}^3$
(3) $\rho_d = 1.72 \text{g/cm}^3$
(4) $\rho_d = 1.84 \text{g/cm}^3$
(5) $\rho_d = 1.63 \text{g/cm}^3$
(6) $\rho_d = 1.61 \text{g/cm}^3$
(7) $\rho_d = 1.59 \text{g/cm}^3$
(8) $\rho_d = 1.66 \text{g/cm}^3$
(9) $\rho_d = 1.73 \text{g/cm}^3$
(10) $\sigma_{3c} = 100 \text{kPa}$
(11) $\sigma_{3c} = 200 \text{kPa}$
(12) $\sigma_{3c} = 400 \text{kPa}$
(13) $\sigma_{1c} = 100 \text{kPa}$
(14) $\sigma_{1c} = 200 \text{kPa}$
(15) $\sigma_{1c} = 400 \text{kPa}$
Figure 4. Testing curves of $G_d / G_{d_{\text{max}}} \sim \gamma$ and $\lambda \sim \gamma$ for different confining pressures and density.

5. conclusion

By analyzing the results of resonance column test of Guyuan remolded loess under different working conditions, the following preliminary conclusions are drawn:

1. The structure of unsaturated loess has a certain influence on its shear strength. During the remolding process, the shear strength of soil decreases due to the restructuring of particles and the weakening of the cementation between particles. With the increase of confining pressure under vibration, part of the overhead macropore collapses, the particles rearrange, and the soil structure weakens.

2. At the same water content, the maximum damping ratio decreases with the increase of confining pressure, and at the same confining pressure amplitude, the damping ratio decreases with the increase of dry density.

3. The dynamic shear modulus ratio increases with the increase of confining pressures and the damping ratio decreases with the increase of confining pressures when the dry density is constant and the same shear strain amplitude. When consolidation pressure is constant, the dynamic shear modulus ratio of loess increases with the increase of dry density and the damping ratio decreases with the increase of dry density at the same shear strain amplitude.

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