Characteristic Research on Dynamic Strength of Remolded Unsaturated Loess Under Different Moisture Content

Yongquan Li
College of Civil Engineering and Architecture, Henan University of Technology, Zhengzhou, 450001, China
*Corresponding author’s e-mail: liyongquan7197213@126.com

Abstract. Luoyang remolded unsaturated loess samples under different natural moisture content were prepared, and then their dynamic strength was tested. The dynamic strength parameters of original loess were obtained when corresponding failure vibration frequency $N_f$ was 10 and 20 times. According to dynamic strength parameters, the present research analyzed changing rules of dynamic strength parameters of remolded unsaturated loess with moisture content and failure vibration frequency. The paper further explores impact of natural moisture content and failure vibration frequency on unsaturated loess dynamic strength index in the region, and fits relationship curve between dynamic strength parameter of unsaturated remodeled loess and natural moisture content, thus propose mathematical expressions. It is shown from the results that there is an obvious linear relationship between dynamic internal friction angle and moisture content. When both dynamic cohesion and moisture content are logarithmized, they will present a good symbol linear relationship.

1. Introduction
Loess is mainly distributed in arid and semi-arid region in Northwest China, and often present non-saturated. The mechanical properties of unsaturated loess are greatly affected by moisture content[1-3]. However, few literatures focus on characteristics of dynamic strength of remolded unsaturated loess under different moisture content. In addition, there is no uniform definition on rock dynamic strength, and there is no unified research method on dynamic strength of remolded unsaturated loess. Therefore, existing researches fail to clearly define rules of dynamic strength of remolded unsaturated loess. However, the dynamic strength of unsaturated loess plays an important role in seismic design, and dynamic strength of remolded unsaturated loess is closely related to engineering construction of the loess plateau[3-4].

In consideration of the above reasons, in order to provide true and reliable reference for the construction and seismic design, the paper standardizes test methods and identification criteria to minimize human disturbance. Loess samples from Luoyang were dried and watered for re-preparation, total six samples were prepared at different moisture contents, and then dynamic strength characteristics were tested and studied. The present research analyzed changing rules of dynamic strength parameters of remolded unsaturated loess with moisture content and failure vibration frequency, as well as dynamic strength properties of unsaturated loess in Luoyang and its influencing factors[5-6]. The study is conducive to further understanding dynamic strength characteristics of unsaturated loess, and guiding seismic design disaster prevention, thereby to provide reference for dynamic strength of unsaturated loess in practical application.
2. Test overview

2.1. Preparation of samples
Screen the grinded air-dried loess samples with a 2mm sieve. Prepare enough samples for testing, stir evenly; measure the moisture content of air-dried sample, then place into moisturizing cylinder. According to the loess volume and moisture content required for the test, the water volume to be added for test should be calculated as follows:

\[ m_w = \frac{m_0}{1 + 0.01\omega_0} \times 0.01(\omega_1 - \omega_0) \]  \tag{1}

Where:
- \( m_w \) - water volume required for preparation of samples;
- \( m_0 \) - Wet loess (or air-dried loess) mass;
- \( \omega_0 \) - Wet loess (or air-dried loess) moisture content;
- \( \omega_1 \) - Wet loess (or air-dried loess) moisture content.

Take sieved air-dried loess samples, spray water uniformly on the loess; fully mix up and place into container, and then tightly close the container for 24 hours. According to dry density and volume, wet loess mass for preparation should be calculated in accordance with the following formula:

\[ m_0 = (1 + 0.01\omega_0) \rho_d V \]  \tag{2}

Where: \( \rho_d \) - dry density of sample; \( V \) - sample volume.

According to desired sample volume and dry density requirements, take a certain mass of wet loess and place in sample compacter with cutting ring. Compact the loess to the desired density with piston.

During the test, process unsaturated loess samples to cylindrical loess samples at a diameter of 50mm, at a height of 100 mm. then the dry density of loess samples is controlled to 1.72g / cm3 after preparation.

2.2. Test Method
The test is performed with DSD-160-type electromagnetic vibration triaxial testing system. Dynamic load is sine wave at a frequency of 1Hz. The test is performed in accordance with Chinese dynamic triaxial test code “SOIL TEST METHOD” (SL237-1999); in accordance with the set value, solidification pressure is applied on the loess samples, at a constant solidification pressure. The solidification test should be completed when axial deformation is not greater than 0.01 mm within 30 minutes.

Dynamic strength test process is as follows: solidify a set of samples (3-4 pcs) in the same stress. Each loess sample are applied with strong, medium and weak dynamic stress, thus to obtain \( \sigma_d \cdot \log N \) curve under the same failure strain. Then change the stress to perform the test repeatedly, thus to obtain three \( \sigma_d \cdot \log N \) curve under three different stresses, as well as three different dynamic stresses at a certain vibration frequency. Therefore, it is available to draw Mohr circle. Then cohesion \( C_\sigma \) and dynamic internal friction angle \( \phi_d \) could be determined. The axial solidification pressures \( \sigma_{\sigma 1} \) are 150, 200, and 250Kpa respectively.

2.3. Failure criteria
Dynamic strength is defined as corresponding dynamic stress value at the time of loess samples failure under dynamic loads. However, how to define the standard “failure” depends on the objective and purpose of dynamic strength test. the general rule is subject to strain value at a certain limit (failure)
(e.g. using 5% as the “failure” strain value). As for loess, it is recommended that the stress at significant turning point of stress-strain curve is taken as failure stress, namely yield standards. The dynamic stress of loess at low humidity state should be the corresponding dynamic stress in time of sample brittle failure. The dynamic stress of loess at high humidity should be the stress at significant turning point of stress-strain curve.

In the loess dynamic strength test, the failure standard is based on the method as described in reference[2], the failure of unsaturated loess under different natural moisture content is considered. In consideration of existing research results and specific circumstances of the test, the failure strain standard is determined that the axial residual strain reaches 4 percent.

3. Dynamic strength test results

Loess dynamic strength index is corresponding to certain failure strain standard and failure vibration frequency in the dynamic test. According to the above fracture strain criteria, it is available to obtain the dynamic stress[3] when the failure vibration frequency is 10 and 20. After processing of experimental data, it is available to calculate undisturbed loess dynamic strength parameters in Table 1 and Table 2.

| Soil samples | 1 | 2 | 3 | 4 | 5 | 6 |
|--------------|---|---|---|---|---|---|
| ω(%)         | 8 | 11| 14| 17| 20| 23|
| c(kpa)       | 34.8| 28.8| 25| 22.3| 20.2| 18.7|
| φ(°)         | 22.9| 21.4| 20.5| 19.4| 18.4| 17.5|

| Soil samples | 1 | 2 | 3 | 4 | 5 | 6 |
|--------------|---|---|---|---|---|---|
| ω(%)         | 8 | 11| 14| 17| 20| 23|
| c(kpa)       | 33.1| 26.5| 23.1| 20.2| 18.4| 16.2|
| φ(°)         | 21.8| 21| 19.9| 18.7| 17.8| 16.9|

Tables 1 and 2 show changing curve between dynamic cohesion $C_d$, dynamic internal friction angle $\phi_d$ and moisture content $\omega$ as well as failure vibration frequency.

Fig.1. Curves of relationships between dynamic cohesion and moisture content.

Fig.2. Curves of relationships between dynamic angle of internal friction and moisture content.
4. Test results analysis

4.1. Dynamic strength characteristics

Figure 1 shows that dynamic cohesion of Luoyang unsaturated loess decreases as the natural moisture content increases. The downward trend of curve slows down gradually with the natural moisture content increases; when the natural moisture content is less than the plastic limit, the curve presents steeper, and the decreasing amplitude of dynamic cohesion increases with natural moisture content. When the natural moisture content is greater than the plastic limit, the dynamic cohesion decreases at a slower rate, and the curve becomes flat; it shows dynamic cohesion decreases with natural moisture content in some stages.

It is shown that changes in the dynamic strength are uneven when the moisture content increases in undisturbed loess, because loess is very sensitive to water; change in moisture content results in degrees in physical and physical-chemical reaction, and makes different impact on connection strength of the structure. When moisture content is less than the plastic limit, loess structure will maintain a high bonding strength, and such the strength drastically reduce as moisture content increases. When moisture content is greater than the plastic limit, the structural strength of loess will be reduced mostly. Then moisture content makes poor impact. When it is less than the plastic limit, the dynamic cohesion will remain higher and increase with the natural moisture content. When it is more than the plastic limit, the dynamic cohesion will become lower and decrease more slowly with the natural moisture content.

It can be seen from Figure 2: the internal friction angle of unsaturated loess from Luoyang decreases slowly as the natural moisture content increases, but at a slight change, it can be considered that moisture content make spoor impact on dynamic internal friction angle of unsaturated loess in Luoyang.

Figure 1 and Figure 2 show failure vibration frequency makes greater impact on the dynamic cohesion. The dynamic cohesion decreases as failure vibration frequency increases. With increase in failure vibration frequency; dynamic internal friction angle decreases slightly, therefore it can be considered that dynamic internal friction angle of unsaturated loess in Luoyang is not affected by failure vibration frequency.

4.2. Relationship between natural moisture content $\omega$ and dynamic cohesion $C_d$

Based on the above analysis, in order to further explore the relationship between moisture content and dynamic strength index of unsaturated loess, it is founded from relationship curve in Table 2 and Figure 1: when dynamic cohesion and natural moisture content are logarithmized, both of them will be linearly related. Figure 3 shows a fitting curve after dynamic cohesion $C_d$ and natural moisture content $\omega$ are logarithmized. The curve can be fitted with a linear equation:

$$\ln C_d = A + B \ln \omega$$

Where: A and B stand for test coefficients.
By fitting the measured data, it is available to obtain the test coefficients \( A = 4.775 \), \( B = -0.589 \) and correlation coefficient = 0.998, when failure vibration frequency of unsaturated loess in Luoyang is 10; the test coefficients \( A = 4.868 \), \( B = -0.658 \), correlation coefficient = 0.997, when failure vibration frequency of unsaturated loess in Luoyang is 20; the fitting results are basically consistent with the measured data. When both dynamic cohesion and moisture content are logarithmized, they will present a good symbol linear relationship.

4.3. Relationship between natural moisture content \( \omega \) and dynamic internal friction angle \( \phi_d \)

According to data in Table 2 and the curve in Figure 2, it is available to fit the curve for relationship between natural moisture content and dynamic internal friction angle. Figure 4 shows the fitting curve for relationship between natural moisture content \( \omega \) and dynamic internal friction angle \( \phi_d \). The curve can be fitted with the following expression:

\[
\phi_d = C + D \omega
\]

(4)

Where: \( C \) and \( D \) stand for the test coefficients.

By fitting the measured data, it is available to obtain the test parameters of unsaturated loess in Luoyang: \( C = 25.49 \), \( D = -0.353 \), fitting correlation coefficient = 0.993 when failure vibration frequency is 10; as well as the test parameters of unsaturated loess in Luoyang: \( C = 24.56 \), \( D = -0.336 \), correlation coefficient = 0.997 when failure vibration frequency is 20; the fitting results are basically consistent with the measured data. The changing rule of dynamic internal friction angle with moisture content shows an obvious linear relationship.

5. Conclusions

The following conclusions are worked out by analyzing the results in dynamic strength test of unsaturated loess under different moisture content:

(1) The moisture content is one of the main influential factors of loess dynamic strength index, which makes greater impact on dynamic cohesion. With increasing natural moisture content, dynamic cohesion significantly decreases; the moisture content makes poor impact on dynamic internal friction angle; with the increase in natural moisture content, dynamic internal friction angle decreases slowly.

(2) Failure vibration frequency makes greater impact on dynamic cohesion. With increasing failure vibration frequency, dynamic cohesion significantly decreases; the failure vibration frequency makes poor impact on dynamic internal friction angle; the dynamic internal friction angle of Luoyang unsaturated loess is not affected by failure vibration frequency.

(3) Under the same natural moisture content, dynamic strength index increase as failure vibration frequency decreases. The decreasing amplitude of dynamic cohesion is more obvious than dynamic internal friction angle.

(4) Both dynamic cohesion \( C_d \) and natural moisture content \( \omega \) are correlated; both dynamic internal friction angle \( \phi_d \) and natural moisture content \( \omega \) are also correlated. When both dynamic cohesion and moisture content are logarithmized, they will present a good linear relationship: \( \ln C_d = A + B \ln \omega \). The changing rule of dynamic internal friction angle with moisture content shows an obvious linear relationship: \( \phi_d = C + D \omega \); this relationship reflects changing characteristics of loess dynamic strength due to change in status.

The above conclusions are helpful to further understanding the characteristics of dynamic strength of unsaturated loess, providing guidance and reference for seismic design and disaster prevention and applications of unsaturated loess dynamic strength in practical works.

References

[1] LUO Y S, XIE D Y, CHEN C L. Test analysis of dynamic failure strength of loess under different moisture conditions[J]. Journal of Xi’an University of Technology, 2001, 17(4): 403-407.
[2] TIAN K L, ZHANG H L, ZHANG B P, et al. Research on static and dynamic Strength of unsaturated loess and the correlation between them[J], Journal of Disaster Prevention and Mitigation Engineering, 2007,27(1):91-95.

[3] LIANG Q G, LI J, LI D W, et al. Some problems on surrounding rock classification of loess tunnels[J].Chinese Journal of Geotechnical Engineering, 2011,33(S):170-176.

[4] YU W L, ZHANG J, ZHANG S F, et al. Advances in quantitative structural research of loess[J]. Hydrogeology Engineering Geology, 2011,38(5):120-127.

[5] WANG J, WANG L M, WANG P, et al. A study of liquefaction characteristics of saturated loess in different regions[J]. Hydrogeology & Engineering Geology, 2011,38(5):54-57.

[6] WANG Q, WANG L M, YUAN Z X, et al. Study on Loess Liquefaction in Tianchuan, Qingshui county, Gansu province Induced by Wenchuan Ms8.0 Earthquake [J]. Hydrogeology & Engineering Geology, 2012,39(2):52-56.