Experimental Study on Dynamic Properties of Loess in Xining Area under Cyclic Loading

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Abstract: In order to study the dynamic characteristics of unsaturated loess in Xining area, this paper use GDS dynamic triaxial apparatus conduct the dynamic triaxial test indoor, the effects of different vibration times, water content and consolidation ratio on the hysteresis loop, dynamic elastic modulus and axial strain of unsaturated loess in Xining area were studied. The results show that: when the vibration times increase, the hysteresis loop from strain axis left moves to right and from sparse become tight; The higher moisture content and consolidation ratio, the hysteresis loop is nearer to large strain direction; With the increase of moisture content, the dynamic elastic modulus decreases of unsaturated loess, and the axial strain increases; With the increase of consolidation ratio, the dynamic elastic modulus and axial strain also increases. The dynamic elastic modulus and consolidation ratio have the same features of increase or decrease, axial strain, moisture content and consolidation ratio also have the same features of increase or decrease. The research results can provide reference for the study of dynamic characteristics and disaster prevention and mitigation of unsaturated loess under traffic load.

1. Introduction
The loess is a kind of yellow powdery soil with columnar joints formed in dry climatic conditions, it distribution area is quite extensive, mainly distributed in Qinghai, Gansu, Shanxi, Shanxi, Ningxia, etc. Among them, the distribution area of loess in Qinghai Province is 24,800 km\textsuperscript{2}\textsuperscript{1}. With the implementation of China's western development strategy, the western economy has been promoted unprecedentedly. The construction of roads and railways has reached a new height, and the construction of roads and railways inevitably passes through the loess area. Therefore, people are also increasingly concerned about the research on the engineering properties of loess under the action of traffic loads, especially the study of its dynamic characteristics.

At present, Huang Bo, Ding Hao etc \textsuperscript{2} studied the dynamic characteristics of soft soil by using half-sine wave simulated train load. Mu Kun and Guo Aiguo etc \textsuperscript{3} studied the dynamic constitutive relation and the attenuation law of dynamic modulus of red clay in the original structure. However, most studies have been conducted on the dynamic characteristics of soft soil, clay and other saturated soils under the action of earthquakes, traffic and wave loads, and less research on the dynamic characteristics of unsaturated unsaturated loess \textsuperscript{4–5}. The loess has a strong structure, and the change of external factors has a great influence on its strength and deformation, especially in the long-term cyclic load such as traffic loads, the damage will be more pronounced \textsuperscript{6–8}. This article will use GDS dynamic triaxial apparatus to simulate the effect of long-term cyclic loading on the dynamic characteristics of unsaturated loess in Xining area, the change of the dynamic characteristics of
unsaturated loess under different influence factors is discussed to make up the deficiency of this research. The study of the dynamic characteristics of unsaturated loess not only has a certain reference value for the correct analysis of its engineering nature, disaster prevention and mitigation, but also has a far-reaching impact on the improvement of people's living standards and rapid economic development in the western region [9].

2. Dynamic triaxial test

In this experiment, the British GDS dynamic triaxial test instrument is adopted, which consists of the following systems: the driving device, the pressure chamber cover and the balance hammer; confining pressure controller; anti-pressure controller; signal regulating device; high speed data acquisition and control card (HSDAC) or GDSDCS- light control system. GDS dynamic triaxial instrument built-in pressure sensor, no correction, high software integration, is a perfect combination of hardware and software, with more accurate stress, strain control mode and other advantages.

2.1 The test soil samples and preparation

The soil sample was taken from the vicinity of Haihu Road, Qinghai University, in Xining City, Qinghai Province. The soil depth was 4 m, artificial exploration wells were used to take soil. The soil samples taken out were wrapped in cling film, the joints were sealed with clear plastic, and then the soil samples were placed in a special soil sampling box and shipped back to the laboratory. The basic physical properties of the loess samples taken are shown in table 1.

| Moisture content /% | Density / (g·cm⁻³) | Optimal moisture content /% | Maximum dry density / (g·cm⁻³) | Liquid limit /% | Plastic limit /% | Plasticity index |
|--------------------|---------------------|----------------------------|-------------------------------|----------------|----------------|-----------------|
| 12.5~13.5          | 1.59                | 15.4                       | 1.73                          | 25.5           | 13.9           | 11.6            |

Place the recovered natural loess clods on the soil compactor and cut the specimens required for the test, observe the level and color of the soil samples during the cutting process, whether there are impurities, wormholes, whether the soil is even or whether there is cracks. Then use the water film transfer method to prepare the required moisture content according to the test requirements, after the fitting, it is kept in a sealed maintenance mold. And let it stand for at least 3 days. The purpose is to make the moisture as uniform as possible in the sample, the preparation of samples is shown in figure 1.

![Fig. 1 The preparation process of sample](image)

2.2 Test plan and steps

 Usually, the traffic load can be simulated sine wave, half sine wave or triangle wave, irregular wave, undrained test is mostly simulated by sine wave, and the drainage test is generally simulated by half sine wave. In this test, a consolidated undrained test method was used, a sine wave was used to simulate the traffic load, and a dynamic triaxial cyclic test loading method was used for load control. The loading frequency is 3 Hz, the vibration amplitude is 20 kPa, and the number of vibrations is 5
000. The test confining pressure is 100 kPa. The two consolidation methods are equal pressure and bias. The consolidation ratio is 1.0 and 1.5, and the moisture content is 14%, 16%, and 18%.

First, the sample was installed, then 100 kPa confining pressure was applied to the pressure consolidation, according to the consolidation and stability criteria in the geotechnical test regulations (SL237-1999) [10], when the change of consolidation and drainage within 1 h is less than or equal to 0.1 cm³ consolidation is completed. The pressure consolidation is before bias consolidation, after the isostatic consolidation is applied, the axial pressure is applied at a predetermined axial strain rate, when the axial pressure is 150 kPa, the bias consolidation is completed. During the consolidation process, the drainage valve is always open. After the consolidation is completed, the dynamic load is applied to start the vibration, the test terminated when the number of vibrations reaches 5,000, and the drain valve is closed during vibration.

3 Test results and analysis

3.1 Hysteresis loop analysis

The soil is a non-ideal elastomer and its dynamic stress (σd) waveform is not synchronized with the dynamic strain (εd) waveform, the dynamic strain waveform lags behind the dynamic stress waveform in time. The corresponding dynamic stress and the dynamic strain value at the same moment in each period are the hysteresis curve [11]. The curves of σd-εd under different vibration frequency (N), different moisture content (ω), and different consolidation ratio (Kc) are shown in Fig. 2.

![Hysteresis loop analysis](image)

(a) Different vibration times  (b) Different moisture content  (c) Different consolidation ratio

Fig. 2 The curves of σd-εd under different test conditions

It can be seen from fig. 2 that, under different conditions, the σd-εd is different, in the increasing process of N from 1, 000 to 5, 000 times, the hysteresis loop is closely spaced, and every 1,000 intervals between the two hysteresis loops are also shrinking. This is because εd increases rapidly when the vibration is just started, and the rate of εd increases gradually as N increases. When the water content and the consolidation ratio increase, the hysteresis loop moves from the left side of the strain axis to the right side. The higher the water content and the consolidation ratio, the closer the hysteresis loop is to the place where the strain is large (that is the right side of the strain axis). Because when the moisture content and the consolidation ratio increase, the σd is constant but the εd is increasing. Because the unsaturated loess in this area belongs to silty clay, its complex viscoelastic plasticity leads to the σd-εd curve is not completely closed [12].

3.2 Dynamic elastic modulus analysis

The dynamic elastic modulus (E_d) is equal to the ratio of σd and εd when the soil is in the elastic deformation stage, that is, the slope of σd-εd curve. Fig. 3 and fig. 4 are the curves of E_d - εd under different test conditions.

Fig. 3 shows that, when the moisture content is constant, the E d of unsaturated natural loess has significant strain softening characteristics. E_d decreases nonlinearly as εd increases, and E_d decreases faster when εd is smaller; E_d decreases as εd continues to increase. When the consolidation ratio is
constant, the same εd is generated, E decreases as the moisture content increases. The reason for this phenomenon is that when the moisture content continuously increases, the dynamic strength of the unsaturated natural loess decreases, and its structure also becomes more easily destroyed. Therefore, if we do not change σd, the moisture content is higher, the εd will be larger, and the E will be smaller.

Figure 4 shows that when the consolidation ratio is constant, the E nonlinearity decreases as εd increases, and as εd increases continue, the decreasing trend of E slows down. When the moisture content is constant, the same εd is generated, E increases as the consolidation ratio increases, and E increases and decreases with the consolidation ratio. The reason for this phenomenon is that the greater the consolidation ratio, the denser the soil is squeezed, and the larger σd is needed to produce the same εd, therefore, σd increases when εd is constant, which leads to an increase E.

3.3 The curves of εd-N analysis

Fig. 5 and fig. 6 are the curves of the axial strain εd and the number of vibrations N under different test conditions. From fig. 5, it is known that at the same moisture content, εd increases as N increases, and εd increases rapidly in the initial period of vibration, and it basically rises linearly, as N increases, the rate of increase of εd slows down and eventually becomes stable. This is in line with the actual situation. the road embankment sinks faster at the beginning of the journey, and then the rate of sinking slows down, eventually, it basically stabilizes and no longer sinks. When the consolidation ratio is constant, in the same situation as N, with the increase in the moisture content, the εd increases. This is because the moisture content increases, the strength of the soil decreases, and if σd is the same, a larger εd will be generated. From a general point of view, the biased consolidation is significantly faster than the increase in the isobaric consolidation εd at each moisture content.
The following factors have been studied in this paper: the dynamic characteristics of unsaturated loess under traffic loads are very complicated and affected by many factors. Only a few factors have been studied in this paper, and has a significant strain softening characteristic. The results will make a great difference.

As shown in Fig. 8, the same consolidation ratio increases $\varepsilon_d$ with $N$, and $N$ has a turning point, the $\varepsilon_d$ rises in a straight line between the initial vibration and the turning point. The increase is very fast. After the turning point, the rate of increase of $\varepsilon_d$ is getting slower as $N$ continues to increase, finally, it basically stabilizes. When the moisture content is constant, the $\varepsilon_d$ increases with the increase of the consolidation ratio when $N$ is constant, and the rate of biased consolidation is much faster than that of isobaric consolidation. Because when the other conditions are not constant, if the consolidation ratio is larger than the large soil samples will be compacted, the initial axial vibration stress will be large, and the resulting $\varepsilon_d$ will increase accordingly, this causes a significant increase in $\varepsilon_d$ in the following vibrations.

4. Discussion and conclusion

Liu Xiaohong, Yang Guolin etc. [13] studied the dynamic constitutive relation and dynamic modulus attenuation model of red clay under cyclic loading, but did not deal with the dynamic properties of unsaturated loess. Different types of soil structure and properties are different, and the experimental results will make a great difference. This paper studies the influence of different experimental conditions on the dynamic characteristics of unsaturated natural loess under traffic loads. The results show that the relationship between dynamic stress and dynamic strain of unsaturated natural loess is nonlinear; the dynamic elastic modulus decreases nonlinearly with the increase of the dynamic strain, and has a significant strain softening characteristic; the dynamic strain increases nonlinearly with the vibration. The accuracy of the GDS dynamic triaxial apparatus is very high. Using it for testing, the recorded data is more accurate and the results obtained are closer to the actual situation, it can greatly improve the accuracy of engineering design, thus saving engineering cost. The dynamic characteristics of unsaturated loess under the traffic load are very complicated and affected by many factors. Only a few factors have been studied in this paper, the dynamic characteristics of multi-factor coupling need

![Graphs showing dynamic characteristics under different conditions](image-url)
to be further explored.

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References
[1] Zhou Xiaoyan. Experimental Study on Stress Path of Unsaturated Loess[D]. Yang Ling: northwest agriculture and forestry university, 2008.
[2] Huang Bo, Ding Hao. Dynamic triaxial test simulation of high-speed train loading[J]. Journal of Geotechnical Engineering, 2011, 33(2): 195-202.
[3] Mu Kun, Guo Aiguo. Experimental study on dynamic characteristics of Guangxi Red Clay under cyclic loading[J]. Earthquake Engineering Journal, 2015, 37(2): 487-493.
[4] Liu Bin, Wang Mei,. The study of Dynamic Characteristics Unsaturated Loess under Repeated Loads[J]. Science Technology and Engineering, 2014, 14(30):87-90.
[5] Guo Kexin. Dynamic triaxial test study of unsaturated loess[D]. Xi'an: Chang’ an University, 2015.
[6] Shao Shengjun, Tao Hu etc. Study on the research and application of loess structural mechanics[J]. Rock and Soil Mechanics 2011,32(S2):42-50.
[7] Ye Chaoliang, Zhu Yongquan etc. Experimental study on the anisotropic and unloading deformation characteristics of intact loess[J]. China Railway Science, 2014,35(6):1-6.
[8] Zhou Wenquan, Leng Wuming, etc. Dynamic characteristics and skeleton curve model of saturated coarse-grained soil under cyclic loading of low confining pressure[J]. Rock and Soil Mechanics, 2016, 37(2): 415-423.
[9] Zhang Jun, Zheng Junjie etc. Study on dynamic characteristics of saturated compacted loess under cyclic loading[J]. Journal of Geotechnical Engineering, 2013, 35(S1): 322-327.
[10] Ministry of Water Resources of the People's Republic of China. Water conservancy industry standard: SL 237-1999[S]. Beijing: China Water Conservancy and Hydropower Press, 1999.
[11] Huang Zhifu. Experimental study on dynamic characteristics of silt embankment under cyclic loading[D]. Tianjin: Tianjin University, 2011.
[12] Liu Ganbin, Fan Siting etc. Development and Application of Temperature Controlled Dynamic Triaxial Test Device[J]. Chinese Journal of Rock Mechanics and Engineering, 2015, 34(7): 1345-1352.
[13] Liu Xiaohong, etc. Dynamic Constitutive Relation and Dynamic Modulus Attenuation Model of Red Clay[J]. Hydrogeology and Geology Engineering,2011,38(3):66-72.