Study on dynamic stress-strain response law of frozen saline soil

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Abstract. The subgrade saline soil in a certain area of western Qinghai province was studied, based on the British GDS dynamic triaxial test system, the dynamic triaxial test under laboratory test was carried out to study variation dynamic stress-strain and dynamic shear modulus under the different temperature, frequency and confining pressure. The test results show that the dynamic stress-strain relationship is significantly affected by temperature change under cyclic dynamic load, followed by frequency and confining pressure. Under the same strain amplitude, the lower the temperature, the larger the dynamic shear modulus. When frequency and confining pressure increase, dynamic shear modulus also increases. Whereas, the influence of confining pressure on the dynamic shear modulus is more obvious, and the backbone curve development trend is steeper. Both maximum dynamic shear modulus and final shear stress amplitude increase with the frequency increases when temperature and confining pressure remain unchanged. Meantime, the maximum dynamic shear modulus curve is a convex shape, and the final shear stress amplitude curve is a convex shape at positive temperature,while which a concave shape at negative temperature. At constant frequency and confining pressure, the maximum dynamic shear modulus and final shear stress amplitude increase with the decrease of temperature. Curves of change trend are slower above 0℃, and steeper below 0℃.

1. Introduction

Qinghai is located in northeast Qinghai-Tibet Plateau. Due to its unique climatic environment and geological features, saline soils are widely distributed in the territory. The salt content of saline soil in Qinghai is about 3.0296\%, and the maximum can exceed 7.0\% [1]. With the construction of "Belt and Road" and the continuous development of the economy in the western region, the construction of infrastructure, especially transportation infrastructure, has become the focus of engineering. However, under the infection of special climatic conditions, traffic dynamic load, low temperature, freeze-thaw cycle and other factors, there are many diseases on the roads in the salty area of Qinghai. Such as hygroscopic softening, erosion and leaching on the slope surface of saline soil embankment, melting settlement of the road subgrade, irregular deformation, peeling, cracking and falling off of pavement and etc.

At present, the research on saline soil were mainly focused on the basic physical properties and damages to structures, such as corrosion, salt swelling and dissolution [2-6]. There are few researches studied the dynamic characteristics of saline soil under the different temperature. When highway and railway projects in frozen saline soil areas are constructed, it is necessary to focus the special physical, thermal, mechanical properties and dynamic load specificity of saline soil under different temperature conditions [7]. In this paper, the saline soil with high sulfate content in a certain area of western Qinghai was studied, and the dynamic stress-strain response at the different temperatures, confining
pressures and dynamic load frequencies was analyzed. The improved Hardin hyperbola model [8,9] was used for fitting the dynamic stress-strain curve. The response laws of dynamic shear modulus and dynamic shear stress amplitude under different experimental conditions were investigated. In order to provide a further reference, the dynamic characteristics of saline soil with different salinity and types should be considered.

2. Experiments

2.1 Sample preparation and test equipment
The soil samples of this test were taken from the roadbed of a heavy saline soil area in western Qinghai. According to the Test Methods of Soils for Highway Engineering (JTG E40-2007) promulgated by the Ministry of Transport, China. basic physical property parameters of the saline soil samples are shown in Table 1. According to the test results, the SO\textsubscript{4}\textsuperscript{2-} ion content of the soil sample is 3.9468%, containing 0.1481% Cl\textsuperscript{-} ion. Therefore, this soil is a sulphate saline soil. During the test, the remolded samples were prepared according to the optimum moisture content and the maximum dry density, height 80 mm and diameter 39.1 mm, dynamic triaxial test was performed at last, which was adopted British GDS dynamic triaxial test system.

**Table 1. Basic physical properties index of test saline soil.**

| Plastic limit(%) | Liquid limit(%) | Plasticity index | Liquid index | Maximum dry density(g/cm\textsuperscript{3}) | Optimum moisture content(%) | Saline soil type name |
|-----------------|----------------|------------------|-------------|-----------------------------|-----------------------------|----------------------|
| 12.44           | 18.22          | 6                | <0          | 1.73                        | 14.17                       | Sulfate silt         |

2.2 Experimental method
In order to obtain dynamic stress-strain parameters of different conditions, five temperature gradients of 3℃, 0℃, -5℃, -10℃ and -15℃, and dynamic load frequencies were set of 1Hz, 2Hz and 5Hz in the test, the different confining pressures were 100kPa, 200kPa, 300kPa and 500kPa, respectively. Testing scheme are shown in table 2. During the test of different control conditions, the traffic cyclic load in the form of sine wave is applied to the samples controlled after normal and frozen temperature for 24h [10]. In this study, the termination loading conditions were respectively 5% of the dynamic strain above 0℃ and 10% of the dynamic strain below 0℃ [11].

**Table 2. Test scheme setting.**

| Test n. | 2 | 4 | 6 | 8 | 0 |
|---------|---|---|---|---|---|
| QY1-QY1 | QY13-QY2 | QY25-QY3 | QY37-QY4 | QY49-QY6 |
| Temperature(℃) | 3 | 0 | -5 | -10 | -15 |
| Confining pressure(kPa) | 100, 200, 300, 500 |
| Load frequency(Hz) | 1, 2, 5 |

3. Constitutive relations
Dynamic stress-strain relations in the test was fitted by a modified Hardin hyperbolic model [8, 9, 18]. The calculation formulas of dynamic shear stress amplitude $\tau_d$, dynamic shear strain amplitude $\gamma_d$ and dynamic shear modulus $G_d$ in the dynamic stress-strain curves relations are as follows (1), (2), (3) and (4). Improved Hardin hyperbolic model the equation (1):

$$
\tau_d = \frac{\gamma_d}{\left( a + b \gamma_d \right)^c} \tag{1}
$$

where $a$, $b$ and $c$ are experimental fitting parameters ($a>0$, $b>0$, $c>0$). Dynamic shear modulus
calculation as follow equation (2):

\[
G_d = \frac{\tau_d}{\gamma_d} = \frac{E}{2(1+\mu)} = \frac{1}{(a' + b' \gamma_d)^{\frac{1}{2}}}
\]  

(2)

where, \( E \) is the ratio of the axial dynamic strain amplitude to the dynamic stress amplitude, \( \mu \) is the dynamic Poisson's ratio (which is taken 0.35) \[19\]. When \( \gamma_d \to 0 \) in the equation (2), the equation (3) is obtained, and \( \gamma_d \to +\infty \) the equation (4) is obtained.

\[
G_{d, max} = \frac{G_d}{\gamma_d \to 0} = \frac{1}{a}
\]  

(3)

\[
\tau_{d,ult} = \frac{\gamma_d}{\gamma_d \to \infty} = \frac{1}{b}
\]  

(4)

where, \( G_{d, max} \) is the maximum dynamic shear modulus, \( \tau_{d, ult} \) is the final shear stress amplitude.

4. Experimental results and analysis

4.1 Relations between frequency and dynamic stress-strain

Taking the test temperature of 3℃ and -10℃, confining pressure of 500kPa as an example, the other curves change trend is similar under the other temperature and confining pressure. The dynamic shear stress-strain backbone curve is shown in Figure 1. Under the same temperature and confining pressure, the frequency change has obvious influence on curve. When frequency increases, and the \( \tau_d \) also increases. The relations between the \( G_{d, max} \) and the \( \tau_{d, ult} \) as a function of frequency are shown in Figure 2 and Figure 3. When frequency is increased from 1 Hz to 5 Hz, \( G_{d, max} \) and \( \tau_{d, ult} \) both increase. The increase of \( G_{d, max} \) is 10.6% (232.5~257.1MPa) at 3℃, and 17.1% (943.4~1104.6MPa) at -10℃. The increase of \( \tau_{d, ult} \) at 3℃ and -10℃ is 6.5% (0.31~0.33MPa) and 11.8% (1.61~1.80MPa), respectively. The relation between \( G_d \) and \( \gamma_d \) are shown in Figure 4. When the \( \gamma_d \) is uniform, the frequency increases accordingly, the variation of initial stage -10℃ is gentler than that of 3℃.

![Figure 1](image1.png)
Figure 1. The backbone curve of dynamic shear stress-strain under different frequency.

The results show that temperature change at 3℃ may be mainly related to the flow of the viscous water film in soil sample. The magnitude of load frequency reflects the speed of loading rate \[12,13\], when the frequency is small, the load rate is slow. The flow and rearrangement of the water film in soil is easy to occur, soil sample is deformed greatly, so \( G_d \) is small; when frequency becomes larger, the load rate becomes faster, the water film flow and rearrangement in soil are less likely to occur, and the deformation is less. Therefore, \( G_d \) is large. However, the sample at -10℃ has been frozen, soil particles and ice crystals are prone to plastic deformation and rearrangement at a small frequency \[14,15\]. The soil deformation is large, the stiffness is weakened, so \( G_d \) is small; when the load frequency becomes large, the plastic flow and rearrangement of soil particles and ice crystals do not completely occur, the soil deformation is small, and the rigidity is enhanced, so \( G_d \) is large.
4.2 Relations between temperature and dynamic stress-strain
The test frequency is 2 Hz, and confining pressure is 500kPa, dynamic shear stress-strain relationship at different temperatures is shown in Figure 5. It can be seen from the figure that temperature change has a great influence on the curve. When temperature is above 0℃, the change of $\tau_d$ is not obvious, but the influence of $\tau_d$ below 0℃ is significant. Finally, $\tau_d$ decreases with increase of temperature. The relation between $G_{d_{\max}}$ and $\tau_{dult}$ as a function of low temperature is shown in Figure 6. The varied trend of $G_{d_{\max}}$ and $\tau_{dult}$ above 0℃ is slow, and below 0℃ is obvious. $G_d$ and $\gamma_d$ with the temperature change are shown in Figure 7. The $G_d$ corresponding to the same $\gamma_d$ increases significantly with the temperature is lowered, when $G_d$ above 0℃is less than greatly below 0℃. The main reason is that when water content of soil sample is constant, the temperature is lowered, and water in the soil pores freezes as the ice crystals increase, which increases the adhesion between soil particles and ice crystals, and the bite force of soil particles is also enhanced [16]. Therefore, the amount of soil deformation is reduced, the rigidity is increased, and $G_d$ is increased.
4.3 Relations between confining pressure and dynamic stress-strain

The test frequency is 1 Hz and temperature is -10°C of dynamic shear stress-strain relationship under different confining pressures ($\sigma_3$) is shown in Figure 8. The relationship between $G_{dmax}$ and $\tau_{dult}$ with confining pressure is shown in Figure 9. Therefore, other conditions being equal, when the confining pressure increases from 0.1 to 0.5 MPa, the $\tau_{dult}$ and $\gamma_d$ increases significantly. The results show that the relationship between $G_{dmax}$ and $\tau_{dult}$ along with $\sigma_3$ are nonlinear, and have different change trends. The relations curve between dynamic shear modulus and dynamic strain amplitude with different confining pressure is shown in Figure 10, it can be seen that $G_d$ increases with the increase of $\sigma_3$. The increase of $\sigma_3$ is conducive to freeze the small and medium pores, which is distributed in the fine clusters, and the
micro-frozen fissures are healed gradually [15,17,20]. The pore space is occupied gradually by different shapes of crystals and soil particles suitable for itself, and this process enhances the structural of the whole soil structure. Thus, intensifying the strength of the soil.

5. Conclusions
Some results are analyzed, it can be known that:

(1) In negative temperature stage, the dynamic shear stress strain of the saline soil change significantly. The lower temperature, the steeper backbone curve at the initial stage. In positive temperature stage (0°C, 3°C), the backbone curve changes more gently, when the temperature drops from -5°C to -10°C, $G_{\text{dmax}}$ increases from 867.2MPa to 1008.9MPa. The decrease in temperature has the ability to resist external dynamic loads on frozen saline soil, which has a great relation with the continuous conversion of salt-free water into ice crystals.

(2) When the frequency increases, the corresponding dynamic characteristic parameters also increase. When the frequency increases from 1 Hz to 5 Hz at -10°C, $G_{\text{dmax}}$ increases from 943.4MPa to 1104.6MPa, and $\tau_{\text{dult}}$ increases from 1.61MPa to 1.80MPa. The shear modulus increases by 5.3% over the shear stress amplitude. At the same time, whether or not there is a critical frequency value during the frequency change under the test conditions is a problem that needs further consideration.

(3) The frozen saline soil at -10°C, with the increase of confining pressure, the trend of the backbone curve are uniform, the relationship between dynamic shear stress and dynamic shear strain shows that the influence of confining pressure is obviously higher than temperature and weaker than frequency. The increase in confining pressure obviously promotes to freeze the damage of the saline soil against external dynamic loads.

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