Study on orthogonal test of plateau frozen soil under dynamic load

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Abstract: With the increase in global temperature, the frozen soil in the Qinghai-Tibet Plateau has been degraded to varying degrees, resulting in frequent road disease in the cold area, causing the bearing capacity of the frozen soil subgrade to be attenuated. In order to study the effects of the elevated temperature on the deviatoric stress and strain of the subgrade soil, the loading rate, dynamic stress amplitude, and frequency were introduced to simulate the working conditions of the highway, which ensure the negative effect of loading rate, dynamic stress amplitude, and frequency on the deviatoric stress. Then, using the orthogonal test method, for the 9 samples make the GDS dynamic triaxial test. The test results showed that the vibration frequency is the major effect factor on the deviatoric stress, deviatoric stress increased with the vibration frequency increased; the strain increased with the loading rate increased.

1. Introduction
Unlike conventional soils, frozen soil is a kind of soil which is extremely sensitive to temperature. The physical and mechanical properties of frozen soil change sharply with temperature. Under the background of global warming, the increase of frozen soil temperature leads to degradation, the decrease of bearing capacity of the highway subgrade, resulting in creep and melting. Highway diseases frequently occur. The highway does not reach the design life, which has caused widespread concern among researchers. In order to prevent and control highway diseases, the mechanical properties of frozen soil roadbed under loading rate, dynamic stress amplitude, and frequency are studied. Some data indicate that the physical and mechanical properties of frozen soil are greatly affected by loading rate, dynamic stress amplitude and frequency due to the degradation of frozen soil temperature increase and the mutual transformation of ice and water in the frozen soil[1-4]. In this paper, the most disadvantageous factors are found out by dynamic triaxial test with different loading rates, dynamic stress amplitudes, and frequencies on frozen soil samples. Comprehensive experiments are carried out by many scholars, which are heavy and cumbersome[5-7]. In this experiment, the orthogonal test method is used to select representative test combinations, and the partial test is used instead of the comprehensive test. If the comprehensive test requires 3³=27 tests, only 9 tests are needed for the orthogonal test, which reduces the workload and speeds up the test.

2. Test overview

2.1. Test plan
The soil extraction site is a section of subgrade S101 of Provincial Highway of Guoluo Tibetan Autonomous Region in Qinghai Province. The depth of the soil is the same as the depth of the subgrade. It is determined by particle analysis experiments that the soil is silty clay, and the soil particles are slightly brownish yellow. The measured moisture content of the soil is 18% at the scene. According to the meteorological data of Dari County in recent 40 years, the test ambient temperature is determined to be -10°C. The confining pressure is selected to be 100kPa according to the depth of the site.

The dynamic stress amplitude is determined by the load formula [8]:

- \( P = M_0 a \omega^2 \)
- Use a Roman \( P \) for a vibration load dynamic stress amplitude \( P \)
- Use a Roman \( M \) for an unsprung mass \( M \), value 170kN
- Use a Roman \( a \) for a geometric irregularity vector \( a \), \( a = 2 \text{mm} \) (National highway flatness index)
- Use a Roman \( \omega \) for a vibration circular frequency \( \omega \), \( \omega = 2\pi v/L \), \( v \) stands for the speed of the car
- Use a Roman \( L \) for a geometric curve wavelength \( L \), value 6m

The vehicle speed is 120km/h, 100km/h, and 80km/h, and the dynamic stress amplitude is 0.26kN, 0.4kN, and 0.57kN.

Vibration frequency is determined according to the vibration generated by the vehicle load on the road surface. When the vibration frequency is 1Hz, the vehicle speed is generally 80km/h, so the vibration frequency is 1Hz, 3Hz, and 5Hz.

The loading rate is determined according to the relevant specifications, and is 0.05 mm/min, 0.1 mm/min, and 0.15 mm/min.

In the experiment, the confining pressure and temperature are controlled unchanged, and different dynamic stress amplitudes, frequencies and loading rates are applied to the samples. When the sample saturation reaches the ambient temperature, it is consolidated under uniform pressure. The sample is consolidated in the pressure chamber until the deformation per hour does not exceed 0.01 mm, and the pressure equalization is completed. Set the vibration frequency waveform to a sine wave, and the grading loading keeps the dynamic stress amplitude of each stage equal until the sample breaks or the axial strain reaches 15%. The experimental scheme is shown in Table 1.

### Table 1. Test plan

| Temperature (°C) | Confining Pressure (kPa) | Loading rate (mm/min) | Frequency (Hz) | Dynamic stress amplitude (kN) |
|-----------------|--------------------------|-----------------------|----------------|-------------------------------|
| -10             | 100                      | 0.05                  | 1              | 0.26                          |
|                 |                          | 0.10                  | 3              | 0.40                          |
|                 |                          | 0.15                  | 5              | 0.57                          |

2.2. **Test Instruments**

Test Instrument is GDS Triaxial Test Instrument Controlled by Electric Machine. It can accurately control the axial force and displacement in the dynamic test, realize dynamic cyclic test with load control, and dynamically control the axial load at high frequency while keeping the confining pressure unchanged. The computer control and analysis system of the GDS triaxial apparatus can accurately collect data and dynamically change the real-time display data during the test.

3. **Orthogonal design**

Using \( L_9 (3^3) \) orthogonal table, there are three factors: loading rate, dynamic stress amplitude, and frequency. Each factor has three levels[9]. The test scheme is shown in Table 2.
Table 2. Orthogonal test factors and levels

|   | A frequency (Hz) | B rate of loading (mm/min) | C Dynamic stress amplitude (kN) |
|---|------------------|-----------------------------|--------------------------------|
| 1 | 3                | 0.10                        | 0.57                           |
| 2 | 3                | 0.15                        | 0.40                           |
| 3 | 1                | 0.10                        | 0.26                           |
| 4 | 1                | 0.05                        | 0.40                           |
| 5 | 5                | 0.05                        | 0.57                           |
| 6 | 5                | 0.10                        | 0.40                           |
| 7 | 1                | 0.15                        | 0.57                           |
| 8 | 3                | 0.05                        | 0.26                           |
| 9 | 5                | 0.15                        | 0.26                           |

4. Orthogonal test results and analysis

4.1. Orthogonal test results and analysis

Through the dynamic triaxial test, the data of sample damage or the strain reaches 15% can be got. The experimental data are analyzed by orthogonal test. The analysis results are showed in Tables 3 and Table 4.

Table 3. Design and analysis of biased orthogonal test design

| Deviatoric stress | A       | B       | C          |
|-------------------|---------|---------|------------|
| K1                | 12439   | 11802   | 10770.00   |
| K2                | 10708   | 12556   | 12535.00   |
| K3                | 12740   | 11529   | 12582.00   |
| k1                | 4146.33 | 3934    | 3590.00    |
| k2                | 3569.33 | 4185.3  | 4178.33    |
| k3                | 4246    | 3843    | 4194.00    |
| R                 | 677.3   | 342.3   | 604.00     |

(1) Table 3 shows that the magnitude relationship of the influence of the deviator stress is A>C>B. The major effect factor of the deviatoric stress is the vibration frequency. The second effect of the deviating stress is the loading rate. The least effect of the deviating stress is the vibration amplitude. When the sample is vibrating, the ice in the sample decreases, the pore water content increases, the effective stress decreases, the pore water pressure rises, the deviator stress increases, and the bearing capacity decreases. The most unfavorable combination is A3B2C3.

Table 4. Strain orthogonal test design results and analysis

| Strain | A       | B       | C       |
|--------|---------|---------|---------|
| K1     | 35.90   | 35.26   | 39.08   |
| K2     | 43.16   | 41.34   | 41.81   |
| K3     | 41.28   | 43.74   | 39.45   |
| k1     | 11.97   | 11.75   | 13.03   |
| k2     | 14.39   | 13.78   | 13.94   |
| k3     | 13.76   | 14.58   | 13.15   |
| R      | 2.42    | 2.83    | 0.91    |
(2) Table 3 shows that the magnitude relationship of the influence of the strain is $B > A > C$. The loading rate is the main effect factor of the strain, and the effect of the frequency corresponding to the change is the second, and the effect of the dynamic stress amplitude is the smallest. The strain increased with the loading rate increases. Therefore, according to the results of the range analysis, the most unfavorable combination is $A_2B_3C_2$.

4.2. Orthogonal test optimization

The most unfavorable combination of deviatoric stress is $A_3B_2C_3$. The most unfavorable combination of strain is $A_2B_3C_2$. After theoretical derivation and experimental research, the combination of the most unfavorable interval is $1-3$ Hz, 0.1-0.15 mm/min, and 0.26-0.4 kN. As showed in Figure 1.

From Figure 1, when the frozen soil is destroyed, there is a negative correlation between the deviatoric stress and the vibration frequency, loading rate, and dynamic stress amplitude. There is a positive correlation between strain and vibration frequency, loading rate and dynamic stress amplitude.

5. Conclusion

Through the dynamic triaxial tests of the deviatoric stress and strain relationship of frozen soil under different conditions, the following conclusions are obtained:

1. The loading rate is most unfavorable for the deviatoric stress and strain in the interval of 0.1-0.15 mm/min.

2. The frequency has the most unfavorable effect on the deviatoric stress and strain in the interval 1-3 Hz.

3. The dynamic stress amplitude has the most adverse effect on the deviatoric stress and strain in the interval of 0.26-0.4 kN.

4. In this paper, the influence of biased stress and strain on frozen soil is applicable to a certain extent. It is suggested that in the future highway design and construction in cold regions, the influence of frozen soil degradation on subgrade soils should be fully considered, and the harm of loading rates, dynamic stress amplitudes, and frequencies to subgrade soils should be considered comprehensively in the most disadvantageous sections.
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