Dynamic Shear Modulus of Frozen Soil under Repeated Cyclic Loading

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Abstract. The safety and stability of engineering in cold regions are strongly influenced by the dynamic behavior of frozen soil. The variation of dynamic modulus of frozen soil subjected to repeated cyclic loading were investigated based on the cyclic triaxial tests. The results show that the dynamic shear modulus can be characterized by its average value. The average value of dynamic shear modulus is strongly influenced by the initial bulk stress. Moreover, the influences of temperature and initial moisture content on strength of frozen soil are evaluated. The strength under confining pressure of 0.3MPa is used as the reference strength to reflect the physical and mechanical properties of frozen soil. The relationship between dynamic shear modulus and reference strength is proposed.

1. Introduction

A great many engineering constructions such as railways, highways, pipelines are widely distributed in frozen regions of Europe and East Asia[1]. Extensive previous studies have shown that the safety and stability of the infrastructures constructed in cold regions are strongly influenced by the dynamic modulus of frozen soil[2]. Hence, the dynamic modulus of frozen soil is becoming a subject of prime importance for relevant engineers or researchers. Alhuaindi[3] conducted the resonant-column tests to study the dynamic shear modulus of frozen soil and observed that the dynamic shear modulus of frozen soil was significantly greater (30 or 50 times) than that of unfrozen soil. Ling[4] conducted a series of dynamic triaxial compression tests of frozen soil and the results indicated that confining pressure had a significant effect on dynamic shear modulus. The empirical expression was also formulated to estimate dynamic shear modulus. Vinson[5] studied the effect of moisture content, confining pressure, temperature, amplitude of dynamic stress and frequency of vibration on dynamic modulus of frozen soil. The results demonstrated that temperature had the greatest impact on dynamic modulus. Zhu[6] pointed out that the dynamic shear modulus of frozen soil reached its maximum under the critical frequency (about 6 Hz). Shen[7] discussed the evolution law of rebound dynamic modulus under different confining pressure based on triaxial compressive tests and found out that the dynamic modulus of frozen soil increased with the increase of confining pressure and the decrease of temperature. Luo[8] pointed out that the dynamic modulus of frozen soil increased with the increase of vibration frequency and the decrease of temperature. Wang[9] pointed out that the maximum value of dynamic shear modulus of frozen soil increased evidently with decreasing temperature. The dynamic modulus ratio increased...
with increasing vibration time and decreased with decreasing temperature. Gao[10] found that the dynamic modulus of frozen soil decreased as the dynamic strain increased based on a large number of triaxial tests.

In this study, a large number of triaxial tests of frozen soil under repeated cyclic loading are conducted systematically. The dynamic shear modulus is used as the dynamic characteristic index to evaluate dynamic behavior and the evolution of dynamic shear modulus under repeated cyclic loading is studied. Based on experimental evidence, the computational model of dynamic shear modulus has been produced. Moreover, the effects of temperature and initial moisture content on strength of frozen soil are evaluated. The relationship between dynamic modulus and strength is proposed.

2. Experimental program

2.1. Tested soil and device

The soil used in this study is clay soil which was obtained from the embankment along the Qinghai–Tibet Railway in China. The liquid limit and plastic indices are 19.5% and 8, respectively. Other physical and mechanical indices of the soil can be found in Reference [11]. One specification was adopted in preparation, Code for Soil Test of Railway Engineering (TB10102-2010) and the specimens were made in batches in order to make sure the comparability[1]. The dynamic triaxial tests were performed in the State Key Laboratory of Frozen Soil Engineering of Chinese Academy of Science. The device is the MTS-810 (Material Test System 810) which is equipped with an automatic numerical control system and a data collection system.

2.2. Test conditions and data processing

The test conditions are shown in Table 1 in detail.

Figure 1 shows the typical dynamic stress-strain curve of frozen soil under repeated cyclic loading. As shown in Figure 1, the hysteresis curve is composed of the loading curve and the unloading curve. The hysteresis curve is not a closed cycle because of the accumulative plastic strain. The dynamic strain cannot be completely recovered when the unloading process is completed, that is, the accumulative plastic strain is constantly produced during the loading procedure. The dynamic modulus is defined as the slope of the line connecting the tip point with the end point of the loop.

| Test No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|
| $\sigma_3$ (MPa) | 0.6 | 0.9 | 1.2 | 1.5 | 1.8 |
| $\sigma_d$ (MPa) | 4.2 | 4.5 | 4.8 | 5.1 | 4.5 | 4.8 | 5.1 | 4.5 | 4.8 | 5.1 | 4.8 | 5.1 | 5.4 | 4.8 | 5.1 | 5.4 |

Figure 1 Schematic of dynamic stress-strain curve of frozen soil
The effects of confining pressures and amplitudes of loading on the evolutions of dynamic shear modulus of frozen soil under are shown in Figure 2. The dynamic shear modulus of each specimen decreases first and then increases with increasing accumulative plastic strain. It should be noted that the change is slight and can be neglected. As shown in Figure 2(a), when the amplitude of loading is different, a small increase or decrease of dynamic shear modulus can be found. The same conclusion can be obtained from Figure 2(b)-(e). It is obvious that the amplitude of loading has little effect on dynamic shear modulus. Hence, the dynamic shear modulus can be characterized by its average value. Table 2 shows the average values of dynamic shear modulus of each specimen.

Table 2: Average values of dynamic shear modulus of each specimen

| Test No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Average value (×10²MPa) | 7.3 | 7.2 | 7.4 | 7.4 | 7.6 | 7.4 | 7.8 | 8   | 7.9 | 8.3 | 8.1 | 8.1 | 8.2 | 8.4 | 8.5 |

Figure 2: Evolution of dynamic shear modulus of frozen soil
4. The model of dynamic shear modulus

Figure 3 shows the relationship between average value of dynamic shear modulus and initial bulk stress. Although the amplitude of loading has little effect on average value of dynamic shear modulus, the initial bulk stress which equates to confining pressure in this study has a significant effect on average value of dynamic shear modulus. The average value of dynamic shear modulus increases linearly with the increasing initial bulk stress. When the amplitude of loading equals 5.1MPa, the average value of dynamic shear modulus increases from 740MPa to 840MPa which means a 14 percent growth can be found as the initial bulk stress increases from 0.6MPa to 1.8MPa.

According to experimental results of average value of dynamic shear modulus under different initial bulk stresses, the computational model of dynamic shear modulus can be written as follows:

\[ G = k_1 p_a \left( 1 + \frac{p_0}{p_a} \right)^{n_1} \]  

where \( k_1 \) and \( n_1 \) are dimensionless model parameters with \( k_1 = 5633 \) and \( n_1 = 0.13 \); \( p_0 \) is standard atmospheric pressure with \( p_a = 0.101 \)MPa; \( p_a \) is initial bulk stresses.

5. Influence of environmental conditions on strength of frozen soils

Many investigations show that frozen soil is sensitive to environmental conditions such as temperature and initial moisture content. The strength under confining pressure of 0.3MPa is used as the reference strength to reflect the physical and mechanical properties of frozen soil under different environmental conditions in this study.

5.1. Influence of temperature and initial moisture content on strength of frozen soil

In order to evaluate the influences of temperature and initial moisture content on strength of frozen soil in more detail, a series of triaxial compression tests under confining pressure of 0.3MPa are performed. Table 3 shows the test conditions and results. As shown in Table 3, the reference strength of frozen soil increases linearly with the decrease of temperature from Table 3. Furthermore, the higher the initial water content, the greater the reference strength of frozen soil. The possible reason is that the bonding strength of ice increases considerably with the increasing initial water content or the decreasing temperature.

| Test No. | S01 | S02 | S03 | S04 | S05 | S06 | S07 | S08 | S09 | S10 |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Temperature (°C) | -3  | -5  | -7  | -9  | -11 | -13 | -5  |     |     |     |
| Initial moisture content (%) | 14  | 11  | 12.5| 15.8| 18.3|     |     |     |     |     |
| Peak strength (MPa) | 3.42| 4.25| 5.44| 6.79| 7.5 | 8.29| 2.86| 4   | 4.7 | 5.23|
5.2. The relationship between dynamic shear modulus and strength

Test groups A and B under confining pressure of 0.6MPa are conducted to evaluate the effects of temperature and initial moisture content on dynamic shear modulus of frozen soil. The test conditions are listed in Table 4.

| Test group | Test No. | Amplitude of loading (MPa) | Initial moisture content (%) | Temperature (℃) |
|------------|---------|---------------------------|----------------------------|-----------------|
| A          | T01     | 4.2                       |                            | -3              |
| A          | T02     | 4.2                       |                            | -5              |
| A          | T03     | 4.5                       |                            | -5              |
| A          | T04     | 4.8                       |                            | -5              |
| A          | T05     | 5.1                       |                            | -5              |
| A          | T06     | 5.4                       | 14.0%                      | -7              |
| A          | T07     | 5.4                       |                            | -9              |
| A          | T08     | 6.0                       |                            | -9              |
| A          | T09     | 6.6                       |                            | -9              |
| A          | T10     | 6.6                       |                            | -11             |
| A          | T11     | 6.6                       |                            | -13             |
| A          | T12     | 7.2                       |                            | -13             |
| B          | W01     | 4.2                       | 11.0%                      | -5              |
| B          | W02     | 4.2                       | 12.5%                      |                 |
| B          | W03     | 4.8                       | 12.5%                      |                 |
| B          | W04     | 4.8                       | 15.8%                      |                 |
| B          | W05     | 5.1                       | 15.8%                      |                 |
| B          | W06     | 5.4                       | 15.8%                      |                 |

Figure 4 The relationship between dynamic shear modulus and reference strength

Figure 4 shows the relationship between dynamic shear modulus and reference strength. The dynamic shear modulus tends to increase with the increasing reference strength. The reference strength under the same confining pressure can be used as an index to reflect the physical and mechanical properties of frozen soil. The relationship between dynamic shear modulus and reference strength can be calculated by the equation as follows:

\[ G = a_1 \exp(b_1 s_{0.3}) \]  

where \( a_1 \) and \( b_1 \) are dimensionless model parameters with \( a_1 = 411.6 \) and \( b_1 = 0.13 \); \( s_{0.3} \) is strength under confining pressure of 0.3MPa.
6. Conclusions

The dynamic shear modulus of frozen soil was investigated based on the triaxial tests in laboratory in this study. The results show that (1) when the amplitude of loading changes, a small increase or decrease of dynamic shear modulus can be found; (2) the average value of dynamic shear modulus of frozen soil increases linearly with the increasing initial bulk stress; (3) the reference strength of frozen soil increases linearly with the decreasing temperature; (4) the dynamic shear modulus tends to increase with the increasing reference strength.

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