A Review of the Dynamic Behaviour of Frozen Soils

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ABSTRACT: The dynamic response of frozen soils is one of the significant factors that should be taken into account when designing and constructing infrastructures in cold regions. This paper firstly reviews the state-of-the-art dynamic testing techniques including dynamic uniaxial/triaxial test, resonant column test, wave velocity test and the SHPB test. Then the correlations of dynamic indexes for frozen soils with test conditions are analyzed i.e., dynamic modulus, dynamic strength, damping ratio as well as dynamic Poisson's ratio. The typical stress-strain relationships for frozen soils under dynamic loading are summarized such as empirical models, creep modeling and strength criterion for frozen soils. Finally promising prospects of the study in this paper is suggested.

KEYWORDS: Frozen soils, Dynamic modulus, Dynamic strength, Damping ratio, Empirical model

1. INTRODUCTION

Many engineering problems in cold regions engineering are closely related to the mechanical characteristics of underlying frozen soils under dynamic loads (Lai et al., 2009). Dynamic loads are those that strongly depend on loading duration and that act within a small interval of time or quickly change in magnitude or direction (Siddiqi, 2012). According to the loading duration and amplitude of dynamic stress, three kinds of dynamic loads are generally encountered in cold regions, i.e., earthquake forces, blast loadings and traffic loads. The quake-prone areas are widely distributed in the Qinghai-Tibetan plateau in China (Xu et al., 2005). The landslide, ground crack, liquefaction and subsidence of foundations are frequently encountered in this area, which brought tremendous threat to humans' life and property safety. Due to the tremendous energy released from earthquakes, it is still a challenge to accurately evaluate the seismic responses of frozen ground up to now. Besides, the explosion, as one of the blasting loads, obviously affects surrounding soils around the detonation point within a short duration (Xie, 1988). Moreover, the traffic load which usually imposes a cyclic pressure on embankments is one of the main causes for additional settlement and roadbed crack in permafrost regions. Thus, the reliable service performance of cold regions engineering requires a clear understanding of the dynamic mechanical properties of underlying frozen soils (Lai et al., 2009).

However, due to the particular material composition of frozen soils, as well as its correlations with vibration frequency, amplitude of dynamic stress, time and temperature, changes in dynamic properties of frozen soils have not been paid as much attention as other aspects of frozen soil mechanics. Most of studies focused on the physical and mechanical properties of frozen soils under static or quasi-static loading conditions, including strength behaviors (Ting et al., 1983; Zhu and Carbee, 1984; Ma et al., 1993; Qi and Ma, 2007), frost heave with or without water supply (O'Neill, 1983; Peterson and Krantz, 2003), thaw consolidation (Aoyama et al., 1985; Foriero and Ladanyi, 1995; Yao et al., 2012) and rheological effects (Ladanyi, 1983; Ma et al., 1994; Lai et al., 2009; Wang et al., 2011). A general review of mechanical research on frozen soils given by Lai et al. (2013) clearly addresses the significance of dynamic performance of frozen soils and the dynamic responses of frozen ground engineering should always be concerned when designing and constructing infrastructures in cold regions. This paper aims to provide a general review of dynamic mechanical properties of frozen soils, as well as some empirical models for the dynamic responses of frozen soils.

2. DYNAMIC TESTING TECHNIQUES

Experimental studies on frozen soils were primarily carried out under static or quasi-static loading conditions. As for the dynamic test, it includes four main types of testing methods, i.e., the dynamic uniaxial test (He et al., 1993; Lee et al., 2002), the dynamic triaxial test (Zhao et al., 2003), the resonant column method (Al-Hunaidi et al., 1996) as well as the wave velocity method (Nakano et al., 1972; Nakano and Amold, 1973). Of which, the former two methods are appropriate for the cases at large strain and low frequency states and the seismic load can also be simulated during testing (Xu et al., 1998). Creep testing under constant amplitude of dynamic load can also be performed on frozen soils by the two kinds of methods (Zhao et al., 2002). The resonant column method is one of the typical nondestructive testing methods based on the principle of resonance. The dynamic modulus can be determined based on the resonant frequency, specimen size and boundary condition while the damping ratio of soil by free vibration column test. This method was usually employed in the small-strain and high-frequency conditions. As far as the wave velocity method is concerned, the travel times of P- and S-waves together with the distance from the source to the receivers were measured and then the dynamic elastic modulus and the dynamic shear modulus can be obtained by the following empirical equations:

$$E_d = \frac{3\rho V_s^2\left(V_l^2 - \frac{4}{3}V_s^2\right)}{V_l^2 - V_s^2} \tag{1}$$

$$G_d = \rho V_s^2 \tag{2}$$

where, V_l and V_s are the velocities of P- and S-waves, respectively; ρ is the density of the medium.

The split Hopkinson pressure bar (SHPB), as shown in Figure 1, was firstly used in testing dynamic properties of metallic materials. Due to its explicit principle and convenience in operation, it was then extended in dynamic testing of rock, ceramics and concrete. In recent decades, this method has been introduced to frozen soil mechanics. Lee et al. (2002) performed a series of laboratory tests on the Alaskan frozen soil by using SHPB. The SHPB set-up consists of three main parts, i.e., a striker bar, an incident bar and a transmission bar. The elastic compression waves generated by impacting the striker bar can be transmitted through the specimen and captured by the strain gages in the incident and the transmission bars. Based on the one dimensional theory of elastic wave propagation in a bar and continuity of displacement and stress equilibrium at the interface, the stress, strain and strain rate in the specimen can be derived by the equations proposed by Kolsky (1949) and Lindholm (1964). It was also applied in studying the correlations of dynamic behaviors of frozen soils with temperature (Chen et al., 2005) and stress path (Zhang et al., 2013).

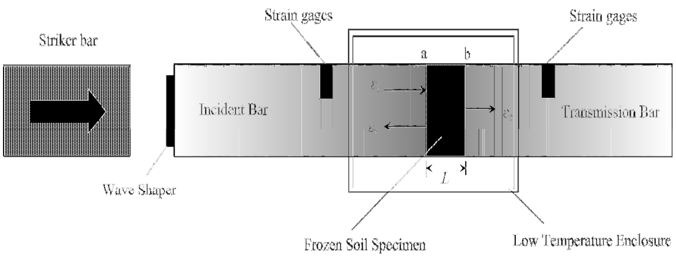


Figure 1 Schematic of the SHPB system used for testing Alaskan frozen soil (Lee et al., 2002)

3. DYNAMIC CHARACTERISTIC INDEXES

3.1 Dynamic modulus

So far two kinds of dynamic modulus have been put forward to provide necessary dynamic characteristic indexes for analyzing the dynamic stability of geotechnical engineering, i.e., dynamic elastic modulus and dynamic shear modulus. For the former, it reflects the tensile and compressive performances of frozen soils during elastic phase and is generally estimated by the ratio of the amplitude of axial load to that of axial strain while as for the latter, the difference in the maximum and minimum stress in a loop, and the difference in the maximum and minimum strain developed in the same loop is recorded and the ratio of these two values refers to the dynamic shear modulus. Here, we firstly take the dynamic elastic modulus as an example to introduce its correlations with test conditions.

1) Confining pressure: Test results indicate that the dynamic elastic modulus of 'cold' frozen soils ($T<-1$ °C) increases with confining pressure while for warm frozen soils ($T\geq-1$ °C) a critical confining pressure exists at which the dynamic modulus approaches to the peak value (Shen and Zhang, 1997a), as shown in Figure 2. We can notice that at low confining pressures, due to the confinement of soil specimen induced by confining pressure, the strengthening effects on soil structure result in a larger dynamic elastic modulus (Li et al., 1979); however, after exceeding the critical value, pressure melting of ice occurs, weakening the bonding effects and causing a decrease in dynamic elastic modulus.

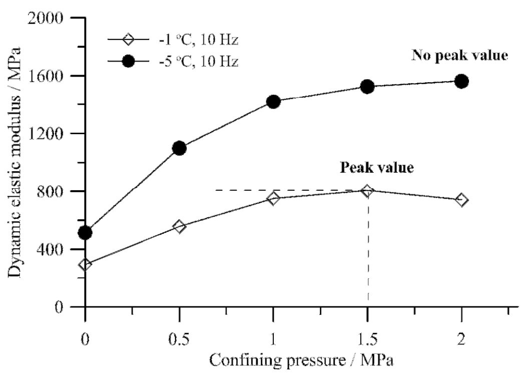


Figure 2 Variation of dynamic elastic modulus at various confining pressures (Shi, 2006)

2) Total water content: In frozen soil mechanics the total water content is a key factor that affects the physical and mechanical properties of frozen soils, including the dynamic characteristics. Test results indicate that the dynamic elastic modulus for frozen fine sand and frozen silty clay increases initially followed by a decrease after a critical water content is reached and the maximum dynamic elastic modulus exist at water contents close to the saturated (Zhao et al., 2003), as shown in Figure 3 (w_{sd} and w_{ss} are the saturated water contents for fine sand and silty clay). Ling et al. (2009) found similar variations of dynamic elastic modulus for frozen clay after dynamic testing on samples at five levels of water content (13%-23%). This is related to the fact that as the water content grows the bonding effect between ice and particles increases but after a critical value the engineering properties of frozen soils tend to exhibit those of ice.

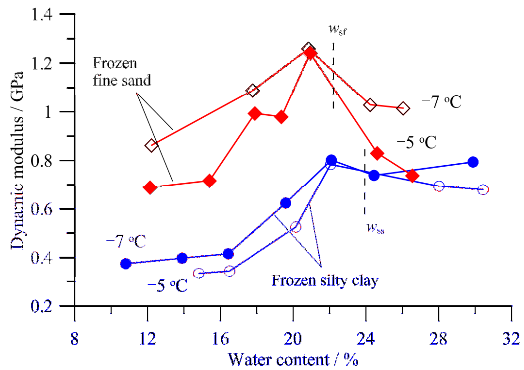


Figure 3 Relations between dynamic elastic modulus and water contents (Zhao et al., 2003)

3) Temperature: Experimental studies on various kinds of frozen soils revealed that a decrease in temperature to some extent reduces the unfrozen water of frozen soils and the cohesive forces that bond ice and particles are enhanced, resulting in a larger dynamic modulus (He, 1992; Xu et al., 1998; Zhao et al., 2003; Ling et al., 2009), especially when ice-water phase change occurs (−5-0 °C) (Wu et al., 2003).

4) Loading frequency: The dynamic elastic modulus for frozen soils is considered to increase with loading frequency (He, 1992; He et al., 1993; Xu et al., 1998), as presented in Figure 4; however, for frozen silty clay and frozen loess, as the loading frequency exceeds 1 Hz, it approaches to a constant value which may be related to the delayed response of the deformation of frozen soils within such a short duration (Luo et al., 2013).

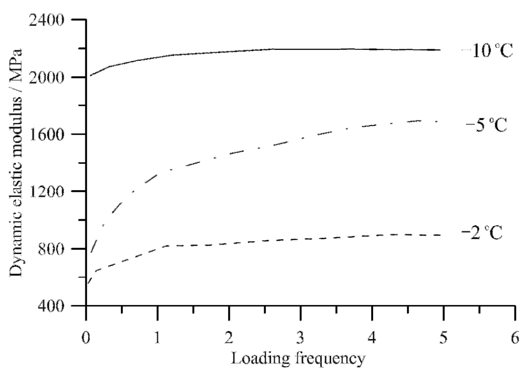


Figure 4 Dynamic elastic modulus at various loading frequencies (He et al., 1993)

5) Dynamic stress amplitude: Previous literatures suggest that the maximum dynamic stress level has little effect on the dynamic elastic modulus of frozen silt (He, 1992; He et al., 1993).
6) Dynamic strain: The dynamic elastic modulus for frozen coarse sand shows a decreasing tendency when a larger axial strain amplitude is applied (Vinson and Li, 1980) but for frozen silty clay it tends to stabilize within a wide range of vibration frequency (0.1-20 Hz) (Luo et al., 2013).
7) Soil type: Cyclic triaxial test results indicate that the dynamic elastic modulus will grow as the content of sand grain grows (Li et al., 1979; Vinson and Li, 1980). Wang et al. (2002) observed similar phenomenon by using the ultrasonic technique. Vinson et al. (1978) and Vilson et al. (1983) found that the dynamic elastic modulus of frozen sand increases with confining pressure (0~1.5 MPa) but little change can be observed for frozen silt and frozen clay.

However, it is worth noting that the definitions of dynamic elastic modulus for frozen soils are inconsistent including the one defined by Hardin and Drnevich (1972) as the slope of the tangent line passing through the origin in stress-strain backbone curves, the resilient modulus for unloading conditions (Shen and Zhang, 1995; Zhao et al., 2003) and that after a certain number of loading cycles (He et al., 1993). Among the above three indexes, we suggest that the one proposed by Hardin and Drnevich (1972) be used in engineering design due to its simplicity and clear physical significance while the other two obtained from stress-strain curves under unloading conditions be applied in the cases when detailed dynamic responses of frozen soils are required.

Taking into account the dependence of dynamic elastic modulus on the amplitude of dynamic strain in equivalent linearization method, Luo et al., (2013) combined the dynamic elastic modulus at different times and a sinusoidally changed strain and derived an equivalent dynamic elastic modulus based on the theory of visco-elasticity:

$$E_{dm} = \sqrt{(c\omega)^2 + E^2} \tag{3}$$

in which, E_{dm} is the maximum dynamic elastic modulus; c is the coefficient of viscosity for dashpot; E is the coefficient of elasticity; ω is the loading frequency.

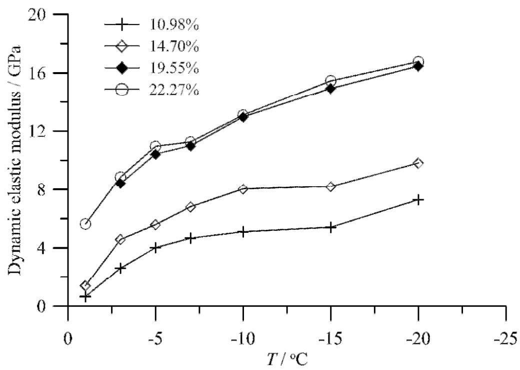
As far as the dynamic shear modulus is concerned, Zhao et al. (2002) found from three kinds of dynamic tests the dynamic shear modulus of frozen soils shows similar changes to dynamic elastic modulus, which manifests that with temperature lowering, it tends to grow with the bonding effects between particles strengthened, as shown in Figure 5.

Moreover, the vibration frequency leads to an increase in the dynamic shear modulus due to the plastic flow and reorientation of ice crystal (Xu et al., 1998). The complex influence of water content on the dynamic shear modulus of frozen soils can also be observed. Wang et al. (2002) found that at lower water contents, the shear modulus of frozen loess tends to increase but for frozen clay at higher water contents, it decreases. Under given test conditions, the magnitude of the dynamic shear modulus in descending order is: frozen sand, frozen loess, frozen clay. Lower soil temperatures to some extent increase the dynamic shear modulus.

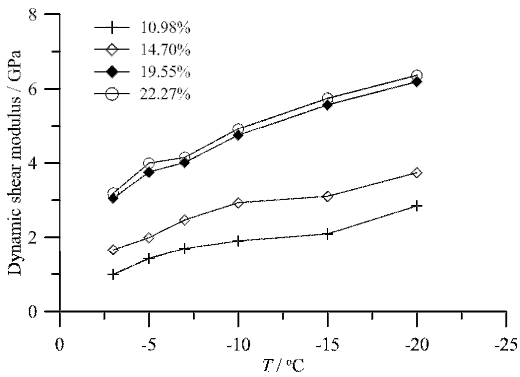
3.2 Dynamic strength

Dynamic strength refers to the dynamic stress when soil specimen attain failure under dynamic load. In the experimental study or even in engineering practice, a certain level of dynamic strain is generally taken as the failure standard and it varies from 2.5% to 10% based on the engineering properties of foundation soils and the importance of the project. Then the strength parameters, i.e., cohesion and angle of internal friction, can be obtained from the Mohr failure envelopes. At a given standard, the dynamic strength is generally considered to be dependent on confining pressure, temperature, loading amplitude, loading frequency and strain rate.

1) Confining pressure: Dynamic strength of frozen soil increases at relatively low confining pressures, which shows the strengthening effects of confining pressure on soil structure; with further increase (6~8 MPa), it approaches to a peak value, followed by a slight decrease (Shen and Zhang, 1997a), as presented in Figure 6. This phenomenon is related to the strengthening effect that prevents the development of micro cracks in frozen soils at low confining pressures while at higher pressures, the pressure melting of ice crystals weakens the soil structure, leading to a lower dynamic strength (Ma et al., 1995). Thus, a critical value might exist, when strengthening and weakening effects counteract. Also, at higher confining pressures, the components of dynamic strength, i.e., cohesion and internal friction angle, tend to decrease at larger confining pressures (Shen and Zhang, 1997b).



(a) dynamic elastic modulus



(b) dynamic shear modulus

Figure 5 Comparison of dynamic elastic modulus and dynamic shear modulus at various temperatures (Meng, 2008)

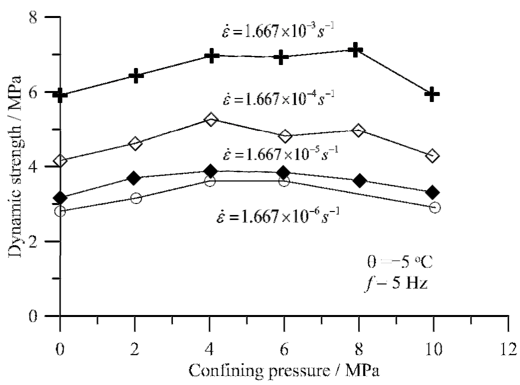


Figure 6 Relationship between dynamic strength and confining pressure (Shen and Zhang, 1997b)

2) Temperature: It is considered that the structural strengthening of frozen soils with decrease in temperature is regarded as the primary cause for the increase in the dynamic strength; however, Shen and Zhang (1997a) from a thorough analysis of dynamic strength at different temperatures found that the variation of unfrozen water in frozen soils may be the internal cause that affect the variation of dynamic strength and strength parameters. Zhang et al. (2008) proposed that the additional temperature increase resulting from the accumulated energy loss of dynamic loading may be the critical factor that affects the variation of dynamic strength. However, there is still lacking some experimental evidences to support this. As for the strength parameters, the cohesion and internal friction angle of frozen soils tend to grow with temperature lowering, especially within the temperature range from 0°C to −5.0°C (Wu et al., 2003), as shown in Figure 7.

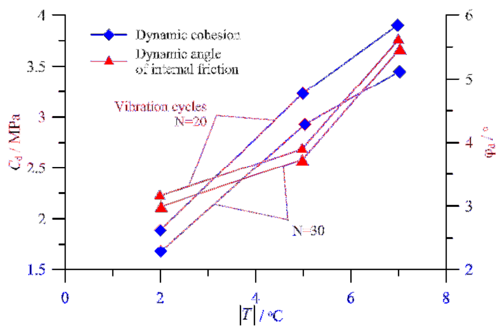


Figure 7 Dynamic strength parameters at different temperatures (Wu et al., 2003)

3) Loading amplitude: The effect of traffic load on embankments in cold regions can be simulated by applying a cyclic dynamic load on soil specimen in laboratory. Zhao et al., (2011) used a sinusoidal dynamic load in uniaxial testing:

$$P(t) = P_0 + P_1 \sin(2\pi f t) \tag{4}$$

From the test results on frozen silt, we found that under a given stress ratio P_1/P_0, the dynamic strength tends to decrease with the increase in the loading cycles; as the stress ratio increases, i.e., at larger loading amplitudes, the dynamic strength is obviously lower than that at lower stress ratios and the time to failure decreases, as presented in Figure 8. However, the work aforementioned is carried out by applying a relatively small amplitude of dynamic load, which is only appropriate for the cases under traffic load. Thus, a systematic study on the dynamic responses of different kinds of frozen soils is required when larger and irregular amplitude of dynamic load are involved, e.g., earthquake or blast loading.

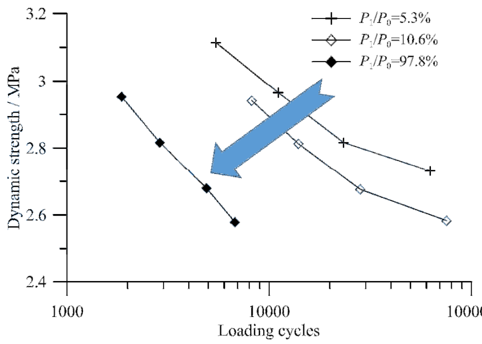


Figure 8 Dynamic strength of frozen silt under different stress ratios (Zhao et al., 2011)

4) Loading frequency: It is considered that when the loading frequency approaches to the intrinsic frequency of material, the resonance phenomenon occurs. He et al. (1993) observed that the dynamic strength of frozen soils has good correlation with the loading frequency and the minimum dynamic strength was reached at a certain level of loading frequency. Shen (1996) from dynamic testing on frozen silt observed a delayed peak stress with the decrease in loading frequency. As to the strength parameters of frozen soils, the cohesion tends to decrease at larger loading frequencies while the angle of internal friction slightly increases (Wu et al., 2003), as illustrated in Figure 9. We can also notice that as the loading frequency increases, the cohesion of frozen soil varies from 1.14 MPa to 1.34 MPa and the angle of internal friction ranges from 13 ° to 13.5°. Thus, the strength parameters of frozen soils, i.e., cohesion and angle of internal friction, can be treated as constant value in practical application.

5)

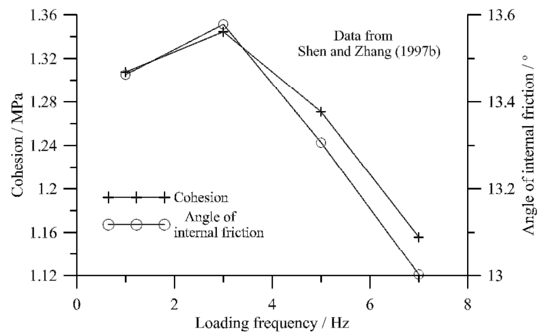


Figure 9 Strength parameters at various loading frequencies

6) Strain rate: Dynamic strength of frozen soils increases with strain rate for plastic failure (Tsytovich, 1985). Shen and Zhang (1996, 1998) further observed a critical strain rate at which the dynamic strength is equal to the shear strength under static stress conditions. As the strain rate exceeds the critical value, both the failure strain and the dynamic strength are larger than that under static stress state while the opposite tendency can also be found when strain rate is lower than the critical. The collapse pattern transiting from plastic failure to brittle failure can be observed with increase in strain rate (Shen and Zhang, 1996).

Compared with the strength of frozen soils under static conditions, the dynamic strength may be larger at higher loading frequencies during testing; however, the cyclic dynamic loading also leads to the weakening of soil structure, resulting in lower dynamic strength and even lower than the strength under static conditions. The coupling effect of these two processes leads to the existence of the critical dynamic strength at various confining pressures, temperatures, loading frequencies and strain rates. As for the loading amplitude, there is still lacking an experimental study of dynamic responses of frozen soils at a wide range of loading amplitudes.

3.3 Damping ratio

Damping in frozen soils primarily reflects the viscosity of ice and particles that was generally estimated by the damping ratio. Damping ratio is an important index in soil mechanics assessing the energy absorption during dynamic loading and is generally estimated by the following equation:

$$\eta = \frac{\Delta W}{4\pi W} \tag{5}$$

in which, ΔW is the area of hysteresis loop; W is the area of triangle OAB, corresponding to the potential energy at the maximum shear strain, as shown in Figure 10.

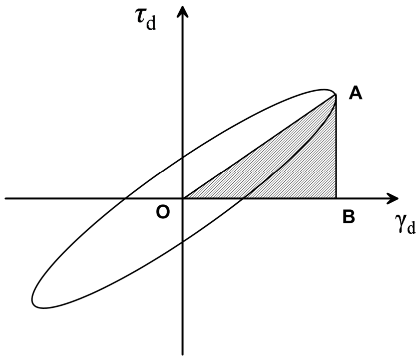


Figure 10 Hysteresis loop

From previous test results we can draw the following conclusions: 1) Damping ratio of frozen soils increases at higher confining pressures, and the magnitude also depends on vibration frequency and soil temperature; 2) As the vibration frequency grows the damping ratio of frozen soils tends to decrease and tends to be a relatively stable value, even at various temperatures and confining pressures, as shown in Figure 11, which indicates that the dynamic load causes the readjustment of soil particles and stabilization of soil structure; 3) At lower temperatures, the plasticity of frozen soils tend to decrease and the energy absorption during dynamic loading cycles reduces, which results in a lower damping ratio, as illustrated in Figure 12 (Li et al., 1979; Vinson and Li, 1980; Zhao et al., 2003; Xu et al., 1998); 4) the damping ratio for many kinds of frozen soils tends to grow with water content but the amplitude of variation is small (Vinson et al., 1978); 5) The higher sand grain content leads to a lower damping ratio of frozen Ottawa sand while water content, confining pressure and axial strain level have little effect (Vinson et al., 1978; Li et al., 1979; Vinson and Li, 1980).

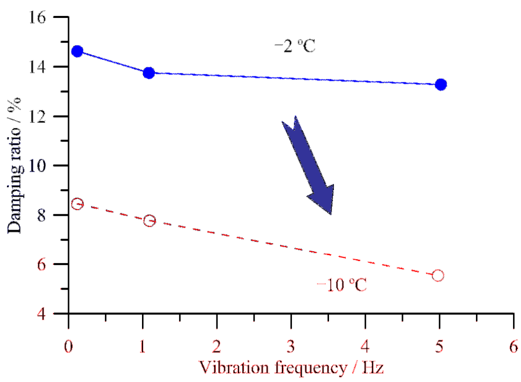


Figure 11 Relationship between damping ratio and loading frequency (Xu et al., 1998)

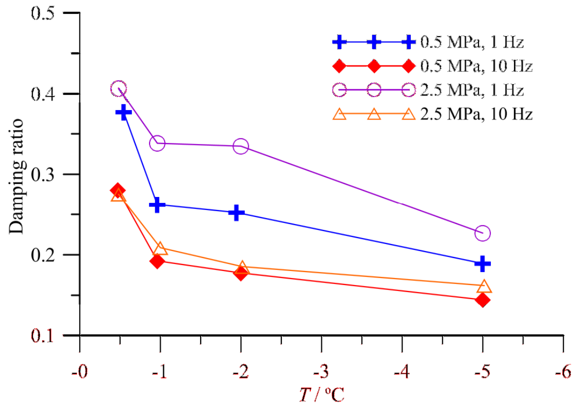


Figure 12 The damping ratio of frozen silty clay at various temperatures (Shi, 2006)

3.4 Dynamic Poisson's ratio

Dynamic Poisson's ratio μ is defined as the ratio of radial strain to axial strain of material under uniaxial tensile or compressive loading (He and Zhu, 1999):

$$\mu = \frac{-\Delta\varepsilon_{\mathrm{r}}}{\Delta\varepsilon_{\mathrm{a}}} \tag{6}$$

in which, $\Delta\varepsilon_{\mathrm{r}}$ and $\Delta\varepsilon_{\mathrm{a}}$ are the strain increment in axial and lateral directions, respectively.

The Poisson's ratio of frozen sand is strongly dependent on temperature but is rarely affected for frozen silt and frozen clay. The Poisson's ratio for different kinds of soils in descending order is: frozen sand, frozen silt, and frozen clay (He and Zhu, 1999), as shown in Figure 13. Wu et al. (2003) suggest the Poisson's ratio for frozen silt and frozen clay can neglect the influence of temperature and a constant value can be used in analyzing the dynamic responses of frozen soils. Xu et al. (1998) based on the two dimensional wave theory proposed a new method to calculate the Poisson's ratio. Wang et al. (2002) found that with increase in temperature or water content, the Poisson's ratio tends to grow and under given conditions, the Poisson's ratio for three kinds of frozen soils in descending order are: frozen clay, frozen loess, and frozen sand, as shown in Figure 14.

Moreover, Xu et al. (1998) put forward a new method to estimate the Poisson's ratio based on the 2D wave theory:

$$\frac{E}{E_c} = \frac{(1+\mu)(1-2\mu)}{1-\mu} \tag{7}$$

in which, E and E_{c} are elastic modulus under unconfined and lateral confined conditions, respectively. In the cases when determining the increments of axial and lateral strain is difficult, this method enables us to conveniently estimate the Poisson's ratio by measuring the dynamic elastic modulus of frozen soils.

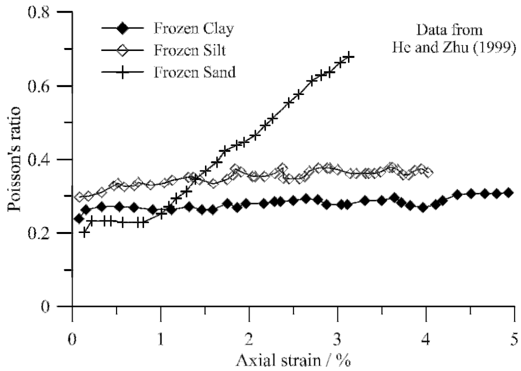


Figure 13 The Poisson's ratio for three kinds of frozen soils

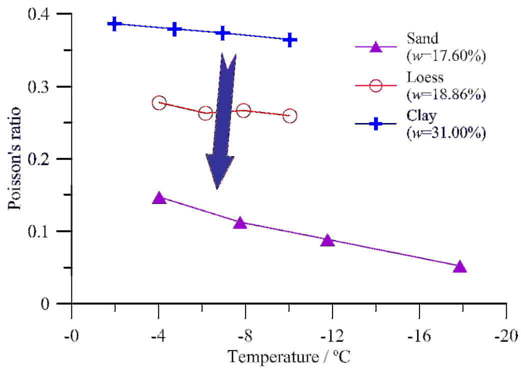


Figure 14 Relationship of dynamic Poisson's ratio vs. temperature (Wang et al., 2002)

4. DYNAMIC STRESS-STRAIN RELATIONSHIP

4.1 Empirical models

Constitutive modeling for frozen soils at static or quasi-static conditions has always been a tough work due to the sensitivity of ice phase to stress state, availability of water and heat budget. Thus, some scholars seek for empirical descriptions of the general stress-strain relationship for frozen soils by mathematically fitting the stress-strain data during dynamic testing.

The hyperbolic model proposed by Hardin and Drnevich (1972), due to its concise model form and simplicity in deriving model parameters by tests, has been frequently used in soil dynamics, which reads:

$$\sigma_d = \frac{\varepsilon_d}{a + b\varepsilon_d} \tag{8}$$

where, ε_d and σ_d refer to dynamic strain and dynamic stress, respectively; *a* and *b* are parameters obtained by test. When frozen soils are concerned, Wu et al. (2003) discussed the applicability of the Hardin-Drnevich model in simulating the dynamic stress-strain curves for some kinds of frozen soils based on statistical analysis.

Gao et al. (2010) investigated the performance of the Hardin-Drnevich model when describing the dynamic elastic modulus of frozen soils and found that for warm and ice-rich frozen soils this model shows poor fitting results. Thus a revised version of Hardin-Drnevich model was proposed for warm and ice-rich frozen soils, which can be described as:

$$\sigma_d = \frac{\varepsilon_d}{a + b\varepsilon_d + c\varepsilon_d^2} \tag{9}$$

where, *a*, *b* and *c* are experimental parameters.

Besides, some empirical laws were established by test such as the hyperbolic model by Xu et al. (1998) and the power function for frozen silt (Shen and Zhang, 1997b).

4.2 Creep modeling under dynamic load

Under a constant dynamic load, frozen soils exhibit obvious rheological characteristics and also attain failure within a certain duration as that under static or quasi-static loading conditions. Three characteristic creep indexes including the minimum strain rate $\dot{\varepsilon}_{min}$, the strain of failure ε_f and corresponding time to failure t_f, were introduced to characterize how creep of frozen soils develop under dynamic load. Experimental results indicate that (He et al., 1995; Zhu et al., 1995; Zhao et al., 2002b): 1) Confining pressure rarely affected the failure strain but a critical value exist at which the time to failure maximizes and the minimum strain rate tends to minimize; 2) at lower temperatures, the time to failure tends to grow while the minimum strain rate and the failure strain decrease; 3) The failure strain and corresponding time to failure tend to decrease while the minimum strain rate increases; 4) As the maximum dynamic stress grows, larger failure strain and minimum strain rate occur while the time to failure decreases.

Following the methods of modeling in conventional soil mechanics, creep modeling under dynamic load primarily focused on the empirical description of creep test curves. He (1992) proposed a dynamic creep model for predicting the primary and secondary creep of frozen soils under uniaxial conditions, which reads:

$$\varepsilon_m = e^{A} e^{B\sigma_{\max}} \left(t^{1/3} + t\right)^{C + D\ln\sigma_{\min}} + E\ln\sigma_{\max} + F\ln f \tag{10}$$

where, σ_{max} and ε_m are the maximum stress and corresponding strain in a vibration cycle, respectively; *f* is the vibration frequency; *t* is the duration of dynamic loading; *A*, *B*, *C*, *D*, *E* and *F* are the temperature dependent parameters.

Zhu et al. (1998) derived an empirical model for frozen soils under triaxial conditions:

$$\varepsilon = A + Bt + Ct^{1/3} \tag{11}$$

where, *t* is time; *A*, *B* and *C* are experimental parameters correlated with temperature, confining pressure and deviatoric stress. The above three terms in Eq. (6) represent instantaneous deformation, viscoplastic flow and attenuated creep, respectively.

4.3 Dynamic strength criterion for frozen soils

The failure criteria used in static stress state cannot be simply applied to dynamic conditions. He et al. (1993) considered the effect of vibration frequency and proposed an empirical strength criterion for frozen loess, which reads:

$$\sigma_f = A + Bf + Cf^2 + D\ln(1 + 1/\sqrt{t_f}) \tag{12}$$

where, t_f, *f* and σ_f refers to the time to failure, vibration frequency and strength of failure, respectively; *A*, *B*, *C* and *D* are temperature-dependent parameters.

Shen and Zhang (1997b) statistically analyzed the deviation between dynamic strength measured and that simulated by the Mohr-Coulomb criterion and found that the increment of unfrozen water during pressure melting is positively correlated with the deviations, which can be written as:

$$\tau = \left(C_0 + \sigma\tan\varphi_0\right) - \left(b_2\Delta W_u^2 + b_1\Delta W_u + b_0\right) \tag{13}$$

where, τ is shear strength; c_0 and φ_0 are dynamic cohesion and internal friction angle when the normal pressure σ is equal to 0 kPa; $\Delta\sigma$ is the variation of strength induced by the decrease in the freezing point of soil; ΔW_u is the variation of unfrozen water caused by the lowering of freezing point; b_0、b_1、b_2 and k are parameters dependent on dynamic internal friction angle. We can see from Figure 15 that the fitted curves calculated by the parabolic criterion show a good agreement with test data.

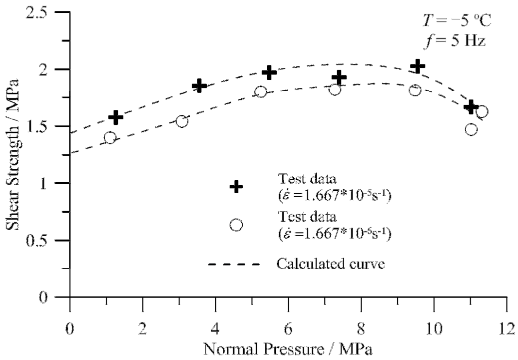


Figure 15 The parabolic strength criterion for frozen silt (Shen and Zhang, 1997b)

However, up to now most of constitutive modeling of frozen soils under dynamic loading conditions have been carried out by using empirical methods. This is related to the fact that when the dynamic load is involved, the hysteresis effect of stress-strain relationship as well as the variation of the aforementioned dynamic characteristic indexes should all be incorporated in modeling. Moreover, previous work on constitutive modeling aims to provide a method to estimate the dynamic responses under simplified wave-form load. This may not be suitable for the cases when earthquake or blasting load is considered. Thus, a systematic study on the dynamic characteristics of frozen soils under larger and irregular dynamic loading conditions is urgently needed in frozen soil mechanics and in further engineering application. Furthermore, the strength criteria under static or quasi-static condition were mostly used and so far the dynamic strength criteria have not been well applied, which may be related to the fact that the relevant study has not been paid as much attention as the other aspects in frozen soils mechanics.

5. CONCLUSIONS

This paper presents a review of dynamic mechanical properties of frozen soils including dynamic testing techniques, typical dynamic indexes and dynamic stress-strain relationship. From previous work we observed that the testing techniques up to now have been successfully applied in investigating the dynamic responses of frozen soils, especially in analyzing the correlations of dynamic indexes with test conditions such as confining pressure, water content, dynamic stress, soil temperature, loading frequency as well as strain/stress rate. When the stress-strain relationship is concerned, some empirical models were introduced, e.g., the Hardin-Drnevich model, the hyperbolic model and the generalized Hardin-Drnevich model. Besides, the creep characteristic indexes of frozen soils under dynamic load such as the minimum strain rate, the failure strain and corresponding time to failure were analyzed. Then some creep models for the cases under dynamic load were listed. The strength criterion is of great significance for establishing a constitutive model for frozen soils, of course includes that under dynamic loading conditions. By incorporating parameters related to the vibration frequency, variation of unfrozen water content and time effect, the strength criteria have been extended to some specific cases.

However, up to now there is still lacking a clear understanding of how frozen soil structure respond when a large-amplitude and irregular dynamic load is exerted, especially when ice-water phase change is involved. Moreover, little work has been reported on these subjects which focused on theoretical application of state-of-art research results in frozen ground engineering activities. Also, constitutive modeling of frozen soils under dynamic load is urgently needed not only to provide reasonable basis for stability analysis of frozen ground engineering but also to facilitate the theoretical study in soil dynamics.

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