THEORETICAL STUDY OF THERMAL DAMAGE IN FROZEN SOIL

by

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Original scientific paper
DOI: 10.2298/TSCI1504419Z

The weakened strength of frozen soil caused by rising temperature can result in thermal damage, which is mainly affected by ice content. A dynamic model for frozen ice is proposed considering temperature and volumetric strain.

Key words: *thermal, unfrozen water, strength, ice, porosity*

Introduction

Frozen soil is a complex porous material. Many studies focused only on the static aspects of frozen soil without considering its macroscopic properties. Research on its dynamic aspects is rare and preliminary, and the main reference is available in Sandia National Laboratories in the USA [1]. In the process of impact loading, the attenuation of ice particles due to temperature change is a type of thermal damages. Though much progress on frozen soil has been achieved [2], much work on effect of temperature, pressure, and strain rate on thermal damage is very much needed, no theoretical model so far can describe such dynamic properties of frozen soil.

In this work, based on theoretical relations, a temperature-volume strain function applicable to dynamic impacts of frozen soil is proposed. Unfrozen water content and effective ice content based on experimental results are used to analyze the phenomenological effect of temperature. In addition, a model is established to describe the thermal damage taking into account the temperature and effective elastic modulus of frozen soil.

State equations

According to [3], material's P-V relation is:

$$P_H^{'} = \frac{P_H \left[1 - \frac{1}{2}\left(\frac{\gamma}{V}\right)\left(V_0 - V\right)\right]}{1 - \frac{1}{2}\left(\frac{\gamma}{V}\right)\left(V_{00} - V\right)} \tag{1}$$

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where V_0 is the initial specific volume of the compact material, V_{00} – the initial specific volume of the porous complex material, and γ – the Gruneisen coefficient.

By a semi-empirical and semi-theoretical derivation [4], the γ-V function relation of a complex medium shown in eq. (2) can be proved:

$$\frac{\gamma}{V}=\frac{\gamma_0}{V_0} \tag{2}$$

The approximation relation shown in eq. (3) can also be proved:

$$\gamma_0 = 2\lambda - 1 \tag{3}$$

In eq. (3), λ is the fitting parameter obtained from experimental data.

A more accurate P-V relation is given [3]:

$$P_H^{'} = P_H \frac{1-\dfrac{\gamma_0}{2}(1-\alpha\delta_S T_H)\left(1-\dfrac{V}{V_0}\right)}{1-\dfrac{\gamma_0}{2}(1-\alpha\delta_S T_H^{'})\left(1-\dfrac{V}{mV_0}\right)} + \frac{\dfrac{\gamma_0}{V_0}(1-\alpha\delta_S T_H)\left(1-\dfrac{1}{m}\right)}{1-\dfrac{\gamma_0}{2}(1-\alpha\delta_S T_H^{'})\left(1-\dfrac{V}{mV_0}\right)} E(V) \tag{4}$$

where m is the porosity, T_H – the fitting parameter dependent on P_H, α – the volume coefficient, δ_S – a simplified operator that can be defined as $\delta_S = -(\alpha B_S)^{-1}(\partial B_S/\partial T)_P$, and B_S – the volume compression modulus in the isentropic state.

For frozen soil, the form of impact adiabatics shown in eq. (4) is an improvement. However, there are very few studies on frozen soil, and therefore, it is difficult to obtain fully reliable data. Some data, for which exact values are required, cannot be supported by experimental results. Thus, a simplified form [4] of impact adiabatics $P-(V/V_0)$ is used here:

$$P_H = \frac{\left(1-\dfrac{V}{V_0}\right)c_0^2}{\left[1-\lambda\left(1-\dfrac{V}{V_0}\right)\right]^2 V_0} \tag{5}$$

where c_0 is the material's sound velocity.

Thermal damage and effective ice content

Damage to a material under the state of impact is caused mainly by nucleation and propagation of cracks; this phenomenon has been studied in terms of concrete and ceramic materials [5]. Some studies [6] have discussed the macro-relations between unfrozen water content and temperature-pressure conditions. Leng *et al.* [7] used calorimetry to conduct studies showing that unfrozen water content can be calculated:

$$W_u = aT^{-b} \tag{6}$$

The effective ice content conforms to the rule of eq. (7):

$$W_i = k_u(W_0 - aT^{-b}) \tag{7}$$

The pressure melting effect [8] is observed in experiments and impact coefficients k_u and λ are introduced. The relation between the effective ice content and volume strain is obtained as:

$$W_i = k_u \left\{ W_0 - a \left[T_0 + \frac{c_0^2}{c_v} \left(\frac{\dfrac{2\theta}{\lambda} - \dfrac{3}{2\lambda^2}}{(\lambda\theta - 1)^2} + \frac{3}{2\lambda^2} - \frac{\ln(1-\lambda\theta)}{\lambda^2} \right) \right]^{-b} \right\} \tag{8}$$

Fitting curves and deciding parameters

At present, most impact experiments [1, 2] of frozen soil use specimens whose water content is 20%, which directly reflects practical situations. Values of the C_0 and λ of frozen soil are fitted according to confining pressure experiments. The equation is shown as eq. (5). The result is $C_0 = 500$, and $\lambda = 3.7$.

After performing the calculations, the constant-volume specific heat of frozen soil is 1200 J/(kgK) and the effective ice content change with volume strain is shown in fig. 1. The relevant values of k_u, a, and b are 0.9, 11.5, and 0.6, respectively.

As shown in fig. 2, the curve rises almost vertically at the beginning. The ice in the frozen soil is divided into two cases: cemented-ice and pore-ice, with cemented-ice damage occurring before pore-ice damage. Generally, the damage threshold value of cemented-ice reflects the occurrence and development threshold of soil microcracks. Subsequently, the curve decreases and shows an inner relation between the stress response and effective ice content after pore-ice damage occurs.

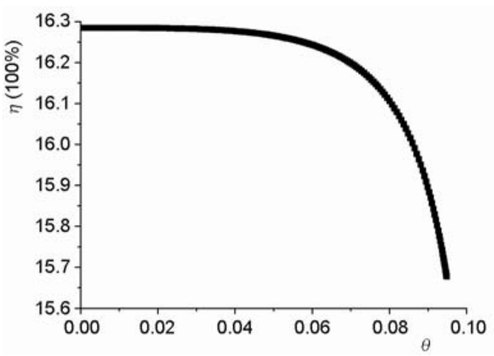

Figure 1. Fitting results for ice content and volumetric strain

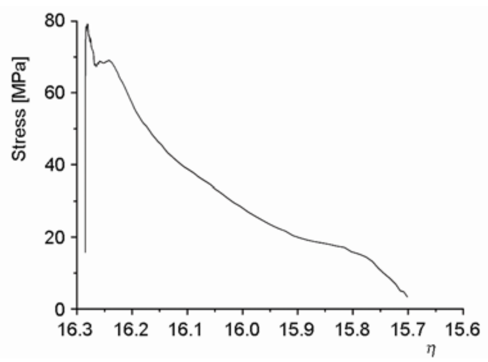

Figure 2. Diagram of ice content and stress

Conclusions

- Temperature variation, *i. e.*, an increase in the adiabatic temperature produces thermal damage; this is due to the striking effect of temperature on the dynamic impact properties of frozen soil.
- The effect of thermal damage appears to affect the effective ice content.
- The methods and equations proposed and discussed in this work could reflect the mechanism and effects of thermal damage well. Furthermore, the relation between equivalent elastic modulus and body strain obtained in this work is very helpful for building and developing a dynamic impact constitutive equation of frozen soil.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 11172251), the Open Fund of the State Key Laboratory of Frozen Soil Engineering (No. SKLFSE201001).

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Paper submitted: October 27, 2014
Paper revised: February 15, 2015
Paper accepted: April 20, 2015