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LABORATORY APPROACH TOWARDS MODELLING THE THAWING BEHAVIOUR OF ARTIFICIALLY FROZEN CLAYS

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I. INTRODUCTION

The need of a rational approach to accurately predict the thaw-settlement has limited the ground-freezing applications to construction activities. Towards this scope, series of laboratory tests were carried out to understand the freezing-thawing behavior of a representative clay element. The behavior of two different clays were investigated and interpreted in light of the state framework. The changes in state, defined by the specific volume and effective stress, during repeated freeze-thaw cycles are discussed and a general relationship has been formulated to describe the irrecoverable behavior at representative element scale.

This paper presents a physical parameter, called the 'frozen state parameter' that combines the influence of void ratio and stress level with reference to an eventual (ultimate) state after cyclic freezing and thawing, to describe the thawing behavior of clays. Results from all-round freeze-thaw tests performed on the commercially available Kasaoka clay and natural Higashi-Osaka clay demonstrated that the volumetric changes due to freezing and thawing normalize well to the frozen state parameter.

II. TESTED MATERIALS AND APPARATUS

The freeze-thaw behavior of two different clays was investigated using a triaxial apparatus modified to permit all-round freezing and thawing under isotropic confining stresses. Samples of high-plasticity Kasaoka clay were prepared by K_0-reconstitution, from a slurry with water content of 100% (i.e. 1.7 times the liquid limit) and compressed one-dimensionally by incremental loading up to three different vertical effective stress (σ'_{v0}) of 50, 100 and 200kPa. The pre-consolidated cakes were trimmed to 30mm diameter and 60mm height for the freeze-thaw tests. The specific gravity, liquid limit and plastic limit of Kasaoka clay were 2.70, 59.6% and 22.5% respectively.

A core of the natural Higashi-Osaka clay, sampled from the depth between 9.55-9.65m, was trimmed to form two specimens with 30mm diameter and 60mm height for the freeze-thaw tests in a triaxial cell. The natural water content, bulk density, void ratio and degree of saturation of an adjacent clay-core close to this depth were 73.29%, 1.558g/cm^3, 1.971 and 99.53% respectively. The freeze-thaw tests were conducted in a temperature and strain rate-controlled triaxial apparatus. This machine was previously used by **[1]** and **[2]** to obtain the shear strength and stiffness characteristics of frozen clays; the apparatus details can thus be found in their reports. The schematic diagram of the triaxial cell is shown in **Fig. 1**.

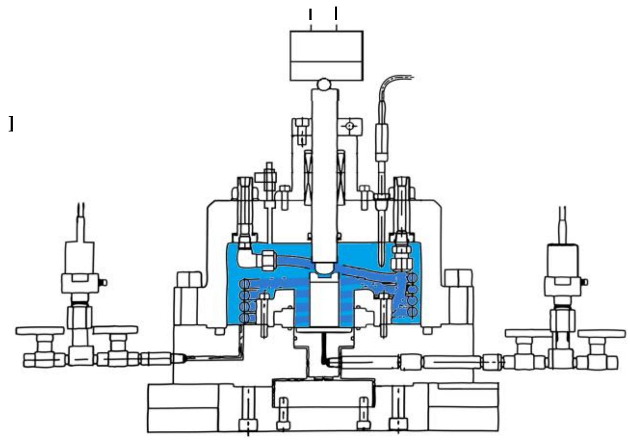

Fig. 1. Vertical cross-section of triaxial apparatus.

III. TESTING CONDITIONS

Two series of laboratory freeze-thaw tests were carried out either by keeping the sample at a constant specific volume after each freezing-thawing episode, or by applying constant external- and back pressures during each freeze-thaw cycles. Accordingly, the tests were grouped under constant-volume test series and constant-pressure test series. The Kasaoka clay samples were tested under both conditions while the natural clay samples were subjected to constant-volume test conditions only.

After setting up the sample on pedestal, and following the saturation process, Kasaoka clay samples were isotropically normally consolidated at room temperature, starting from the residual effective stress assumed to be around $p' = \sigma'_{v0}/3$, through σ'_{v0} and up to $p'_c = 2\sigma'_{v0}$. The natural clay samples were isotropically consolidated, starting from the residual effective stress assumed to be about half of the in-situ effective stress (i.e. $p' = \sigma'_{v0}/2$), and to the in-situ effective stress (i.e. $p'_c = \sigma'_{v0} = 90$kPa) in one case and up to $p'_c = 400$kPa in another case. A constant back pressure of 200kPa was applied during the consolidation process to ensure full saturation. In all the tests, samples were pre-cooled to about +2^{o}C after the normal

consolidation and then quickly frozen (i.e.undrained) to prevent the moisture movement, by replacing the cell water under confining pressures by a chilled refrigerant pre-cooled to about -18°C. After 12 hours, the cell temperature was increased from about -13°C to -2°C and kept stabilized for 24 hours. Thawing was then initiated under confining pressures by replacing the chilled refrigerant inside the cell by a warmer refrigerant kept at room temperature.
The samples were allowed to drain during thawing; the cell temperature was maintained at +2°C, and after about 12 hours, the volumetric deformations stabilized.

At the end of thawing, in the constant-volume test series, the samples were adjusted back to their volume before freezing (see **Fig. 2**), by a careful manual regulation of the back pressure. This way, virtually undrained conditions (closed-system) were imposed to the samples; the effective stress under such condition was termed as the "residual stress" after **[3]**. The process from freezing to residual stress measurement was repeated, each time starting from a constant-volume but from different over-consolidated states, until the volumetric changes got fairly stabilized. The constant-volume testing condition has been illustrated for a 200kPa-consolidated sample in **Fig. 2**.

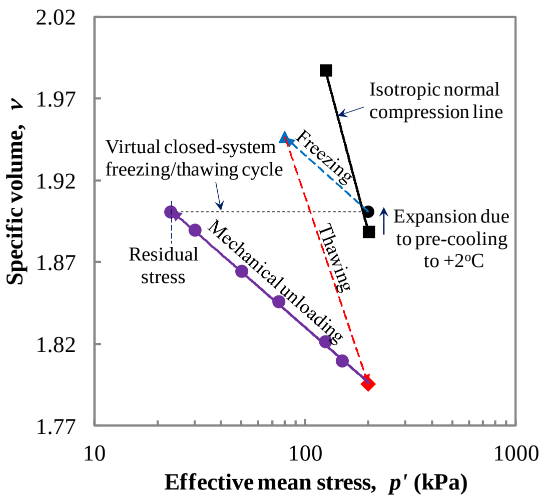

Fig. 2. Illustration of constant-volume test condition adopted in the study.

The constant-pressure tests were carried out without establishing the virtual closed-system after each thawing. Freezing and thawing were thus applied at constant external- and back pressures in each cycle without any particular control over samples' volume. The volumes were allowed to change after each thawing until stable states were attained by the fifth cycle. The constant-presure testing condition has been illustrated for a 200kPa-consolidated sample in **Fig. 3**.

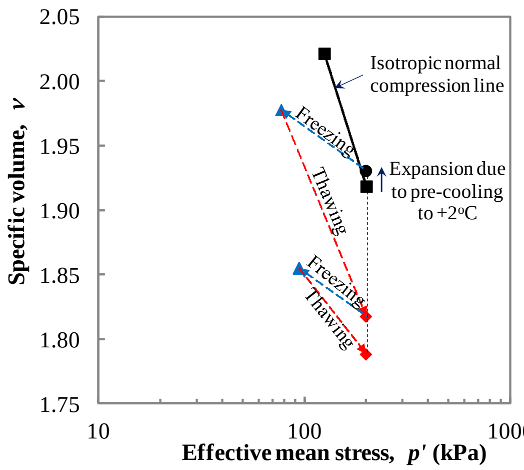

Fig. 3. Illustration of constant-pressure test conditions adopted in the study.

IV. RESULTS AND DISCUSSION

Observed volume-effective stress behaviour during freeze-thaw cycles in Kasaoka clay

The volumes reached after thawing and the residual stresses measured during five freeze-thaw cycles in the constant-volume tests are shown in **Fig. 4**. The numbers in the diagram indicate the state and/or the residual stresses at the end of each cycle, while the different colours demarcate the results of different samples. A small increase in volume was observed due to pre-cooling of the samples after isotropic normal consolidation. As seen from this diagram, the volume decreased after freezing and thawing from normally consolidated and slightly over-consolidated states, while it increased after thawing from heavily over-consolidated states. The residual stress changes followed the trend of volumetric changes after freezing and thawing from different over-consolidated states. The state changes during freeze-thaw cycles were lower at smaller volume-before freezing and at higher confining pressures.

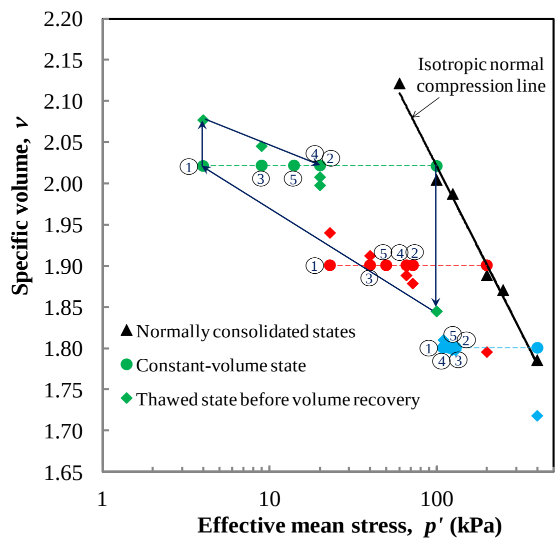

Fig. 4. Change of states during constant-volume freeze-thaw cycles.

The irrecoverable stress changes during the virtual closed-system freeze-thaw cycles and the volumes reached after thawing in constant-pressure tests are shown in **Fig. 5**.

A line connecting the eventual points from all tests was drawn, and extrapolated to intersect the normal compression line (NCL) at a high pressure. This line has been termed as the "ultimate line"; the orientation of ultimate line relative to the NCL suggests that the state-irrecoverability due to freezing and thawing could be inhibited at high confining pressures.

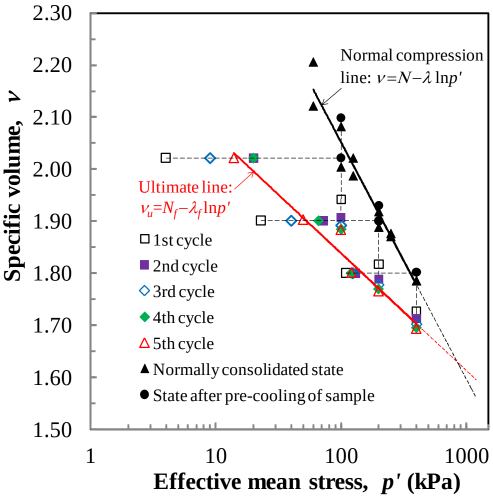

Fig. 5. Residual stresses and volumetric changes during the respective constant-volume and constant-pressure testing conditions.

Modelling approach

Because of its uniqueness, the ultimate line has been taken as a reference to define the state of any clay element. The vertical distance of a clay element from the ultimate line has been characterized as its state, and this measure of state has been termed as the frozen state parameter (ψ_f), analogous to the state parameter (ψ) after **[4]**.

The net volumetric changes after freezing and thawing broadly formed a linear relationship (see **Fig. 6**) with the corresponding frozen state parameters in all tests.

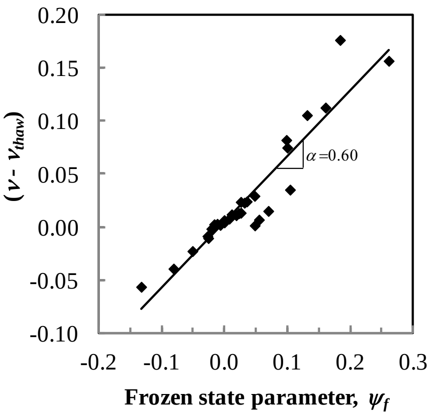

Fig. 6. Volumetric deformations as a function of ψ_f.

The volumetric deformation resulting from thawing of the frozen clays can thus be expressed as:

$$v_{thaw}=v-\alpha\psi_f \quad (1)$$

Here, v is the specific volume before freezing, v_{thaw} is the specific volume after thawing and α is a parameter determined from the experiments. The applications of the model to constant-volume and constant-pressure tests along with the parameters used have been illustrated in **Figs. 7(a) and (b)**.

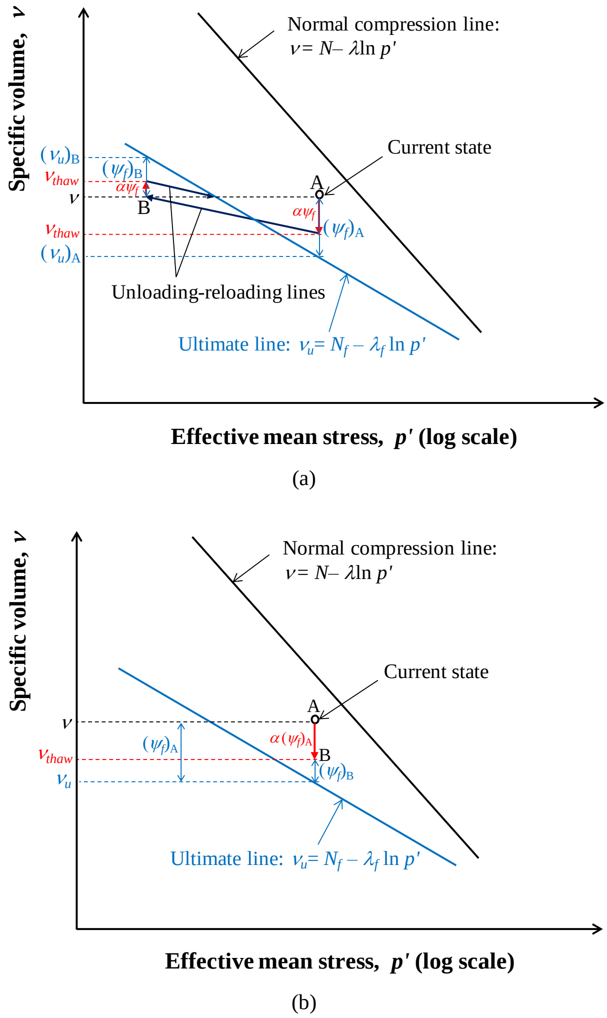

Fig. 7. Illustration of the frozen state parameter, ψ_f and volumetric changes after thawing: (a) constant-volume freeze-thaw test; (b) constant-pressure freeze-thaw test.

Freeze-thaw behaviour of natural Higashi-Osaka clays

The results of two constant-volume freeze-thaw tests on undisturbed natural Higashi–Osaka clay samples are shown in **Fig. 8**. After the isotropic normal consolidation to- and pre- cooling at 90kPa, a sample was subjected to virtual closed- system freeze thaw cycles until the changes got fairly stabilized by the fourth cycle. The sample was then reconsolidated up to 400kPa and freeze-thawed under virtual closed-system conditions for four more times until the changes got stabilized. In the second test, closed-system freeze-thaw cycles were applied after normal consolidation and subsequent pre-cooling at 400kPa until the volumetric changes stabilized by the fifth cycle. The results are broadly similar to those observed in Kasaoka clay i.e. the volume decreased after freezing and thawing from normally consolidated and slightly over-consolidated states while it increased in heavily over-consolidated states. The magnitudes of the state changes during freeze-thaw cycles were higher at the in-situ stress levels compared to those at higher pressures.

The net volumetric changes ($v\!-\!v_{thaw}$) after each freezing and thawing events were plotted against ψ_f to find the parameter 'α' (see **Fig. 9**). Although not very accurate, the proposed model is fairly able to replicate the freeze-thaw behaviour of the tested material.

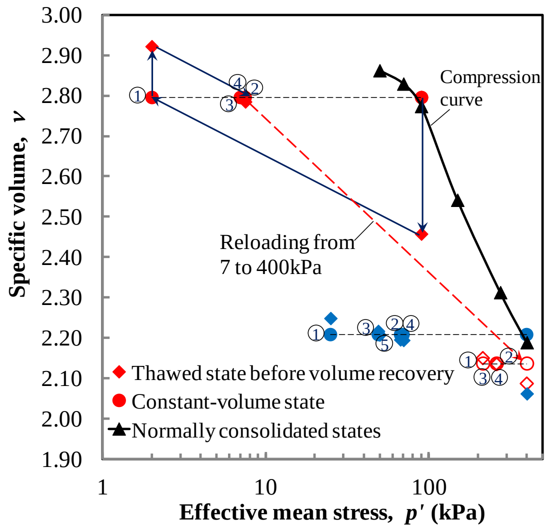

Fig. 8. State changes during freeze-thaw cycles in the natural Higashi-Osaka clay.

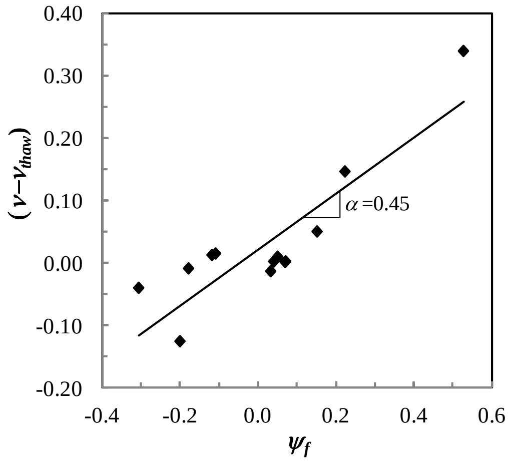

Fig. 9. Estimation of the parameter 'α' in Higashi-Osaka clay.

Implications of the proposed model

The proposed model divides the soil's state in two categories; soils lying to the right of ultimate line are deemed to be in positive states while the states to the left of ultimate line have been considered negative (see the illustration in **Fig. 10**). For the samples with negative state, dilation occurs after freezing and thawing. Mechanical regulation such as imposing the constant-volume conditions after freezing and thawing can however switch the state of sample from negative to positive. As long as the samples remain in positive side, they will continue shrinking until a stable equilibrium is reached after repeated freezing and thawing cycles. The ultimate line could thus be taken as a reference line to demarcate- and model the elasto-plastic swelling-compression or softening-hardening behaviour of soils during freezing and thawing events.

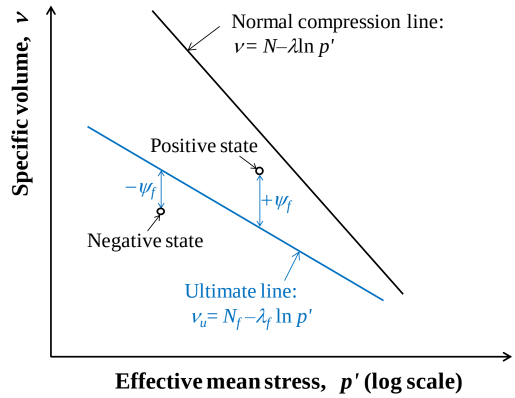

Fig. 10. Illustration of the positive and negative states with regard to freezing and thawing of soils.

V. Conclusions

Freezing and thawing from normally consolidated and/or slightly over-consolidated states decreased the volume after thawing, while the volume increased after freezing and thawing from heavily over-consolidated states. This behavior led to back and forth variation of the effective stresses when constant-volume conditions were imposed at the end of each thawing. Unlike the constant-volume freeze-thaw test results, the volume continuously decreased after each thawing in the constant-pressure tests. Interestingly, the eventual states from both series formed a unique log-linear line in the specific volume-mean effective stress space which seemed fairly independent of the test conditions. The orientation of this line, called the ultimate line, relative to the normal compression line suggested a potential inhibition of the state-irrecoverability due to freezing and thawing at higher confining pressures.

A parameter to characterize the state of clays was presented. The frozen state parameter combines the density and ambient stress level in a unique way for each soil and is relatively easily measured from the laboratory tests. The frozen state parameter allows quantification of the volumetric deformations in freeze-thawed clays using a single variable. With further experimental works, the frozen state parameter concept is expected to lead to the development of a coupled thermo-hydro-mechanical model on freezing and thawing soils that incorporates description of the irrecoverable behavior.

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