Rational design of the artificial ground freezing with state-of-the-art techniques

Ryohsuke Tsuji[1] and T. Yoshida[1]

[1] Technical Research Institute, Kajima Corporation, 2-19-1 Chōfu Tokyo, 182-0036, Japan.

ABSTRACT

The artificial ground freezing is one of the most reliable ground improvement methods for ground excavation, especially in terms of high water cutoff performance. In Japan, it has been applied to more than 600 cases in actual construction since 1962. In recent years, because of the many underground utilities and structures and the demand for deep ground excavation, the importance of ground freezing has increased. We developed several state-of-the-art techniques and practical methods for both rational design and construction.

Keywords: Artificial Ground freezing; frozen soil; Formate; Liquid CO_2; Geo centrifuge

1 INTRODUCTION

The artificial ground freezing method, which costs more than the commonly used ground improvement methods, such as the chemical grouting method or cement-based solidification method, has been considered to provide the most reliable method in terms of water cutoff performance when used for protection of underground excavation projects. In Japan, since its first application to an actual project in 1962, this method has had more than 600 construction results. Because of the diversification in civil engineering projects and increase of projects in great depth in recent years, expectations are mounting higher than ever before on the freezing method. To respond to such trends, the authors have been working to develop freezing method execution technology and design-related technology. This report presents recent developments in freezing technology and frozen soil testing technology.

2 FREEZING TECHNOLOGY

2.1 Freezing system

(a) Quick brine-freezing method

Among freezing systems used for ground freezing projects is the brine system (hereafter “conventional method”) in which brine (calcium chloride aqueous solution) cooled down by an electrically driven refrigerating machine to approximately −30°C is pumped to circulate as coolant through a cooling pipe called the freezing pipe. Except for very short-term, small-scale projects for which liquid nitrogen (LN_2) is used, the conventional method has been a widely used technique, among other reasons, because it can stably cool grounds, it is suitable for large-scale, long-term frozen soil retention, and brine is relatively inexpensive. Depending on the size of the frozen soil site, however, frozen soil preparation takes a long time exceeding one month. Then, in order to accelerate frozen soil preparation, the authors developed a quick brine-freezing method usable at around −45°C. The equipment for this method is configured the same as that for the conventional method, except that the former uses as brine an aqueous solution containing formate as the primary component.

(b) Liquid CO_2 freezing system

The quick brine-freezing method or the conventional method uses a CFC gas or a CFC substitute as the primary coolant, which is used in the refrigerating machine to cool brine as the secondary coolant. This means that the use of refrigerating machines might be restricted if the CFC gas regulations were tightened.

Accordingly, the authors turned our attention to a refrigerating machine of a type that uses ammonia (NH_3), a natural coolant, as the primary coolant and liquid carbon dioxide (CO_2) as the secondary coolant. The liquid CO_2 system resembles the conventional method but uses liquid carbon dioxide (strictly speaking, partially vaporized, gas-liquid mixed fluid) as the secondary coolant. The circulation temperature for liquid CO_2 is −45°C, which is the same as for the quick brine-freezing method. Hence, the frozen soil preparation period will be shorter than with the conventional method. In the conventional method, the secondary coolant/brine absorbs heat from the ground and undergoes a gradual temperature rise (sensible heat absorption into brine) during circulation through the freezing pipe. On the other hand, in the liquid CO_2 system, heat from the ground is absorbed as vaporization latent heat of CO_2. Therefore, the temperature remains constant (−45°C) until the whole amount is vaporized. The use of the more efficient vaporization latent heat than the sensible heat helped to reduce the flowrate of liquid CO_2 through the freezing pipe to approximately 1/10 of that of the conventional method. Moreover, the lower viscosity of liquid CO_2 than that of brine allowed the size reduction of the freezing pipe and the main pipe, as well as the size reduction of the refrigerating machine. After various demonstration experiments, this system has also already been applied to actual work (shield arrival protection work for undersea shield tunnel construction work) and has achieved successful results.

2.2 Simplified freezing technology

The liquid nitrogen (LN_2) system has been among freezing systems in practical use similarly to the conventional method. While the conventional method and the liquid CO_2 system are circulation-type (the secondary coolant returning from the freezing pipe is used after re-cooling by a refrigerating machine), the liquid nitrogen system directly feeds plant-produced LN_2 (−196°C) from a tank truck, a stationary storage tank, a transportable container (ELF), or a similar source to the freezing pipe. Though this system is required to supply LN_2 all the time and hence is unsuitable for large-scale or long-term freezing operation, relatively simple site equipment suffices without the need to install a refrigeration plant. Fig. 1 shows a case in which the inside of a sludge draining pipe is frozen so that the mud pressure shield machine allows safe repair of its internal screw conveyor (sludge draining pipe) receiving water pressure directly from the cutting face. In this case, another significant advantage is that the original condition is recovered by unfreezing and thawing of the pipe. The freezing pipe is applied with a high thermal conductivity plastic material and shielded around with thermal insulator to enhance the freezing efficiency. To give an example from our application track record, a 360 mm OD sludge draining pipe (frozen section length = 500 mm) took approximately 4 hours until frozen (except freeze-retention time). The amount of LN_2 used was approximately 110 kg (equivalent to one ELF). Moreover, this system has been applied to sludge draining pipes up to OD ϕ850 mm and achieved successful results.

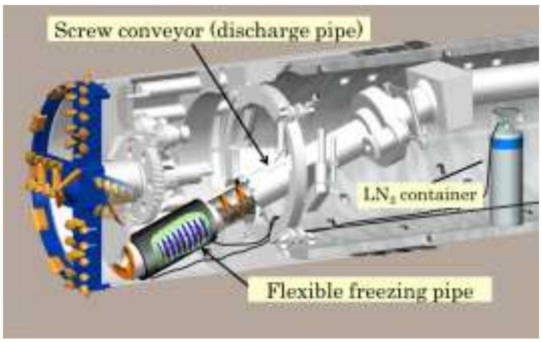

Fig. 1. Makeshift water cut-off technique for screw conveyor (discharge pipe) draining pipe of shield machine

3 FROZEN SOIL TESTING TECHNOLOGY

While there are various experimental investigations conducted in field applications or R&D of freezing methods, laboratory frozen soil tests are normally conducted prior to freezing work, and typical examples are the strength and frost heave tests using a frozen soil loading machine.

3.1 Strength test

We possess the loading machine for the frozen soil and the authors have established a method of comprehensively evaluating the strength of frozen soil by performing compression, bending, shearing, and other tests using this one-stop machine. What follows presents an overview.

When frozen soil strength is expressed in terms of the Mohr-Coulomb failure criteria for cohesion c and internal friction angle ϕ, the unconfined compressive strength (Point C in Fig. 2) and bending tensile strength (Point T) considered in the load-bearing capacity check of frozen soil are geometrically related to the failure criterion line as shown in Fig. 2. In other words, the failure criterion line is the tangent to two Mohr's circles (dia. OC and OT) at the time of failure during an unconfined compression test and bending test. The shear strength S under unconfined conditions is determined as the point of intersection of the failure criterion line and the y-axis. The premise for this assumption, in other words, the linearity of the failure criterion line, was examined by experiment. When the tilted directed shear test developed by the authors is performed (so that the specimen covered with the steel cylindrical confining frame divided along the slit line with tilt angle θ into upper and bottom halves is subjected to unconfined compression and forced slip failure along the slit line), Point D (σ,τ) on the failure criterion line is obtained by breaking down the axial compressive stress C' at the time of failure into the orthogonal component (normal stress σ) and parallel component (shear stress τ) of the slip line.

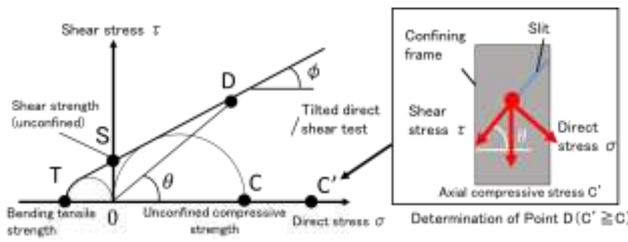

Fig. 2.Interrelationship between unconfined compressive, bending tensile and shear strength of frozen soil

Fig. 3 shows typical results of the abovementioned series of tests. (The tilted direct shear test was conducted at two different tilt angles θ of 45° and 60°.) The failure criterion line appears linear with the shear strength increasing with the confining pressure (normal stress). Therefore, it is considered a practical approach to determine the line and the shear strength (unconfined) S from the unconfined compressive strength C and the bending tensile strength T.

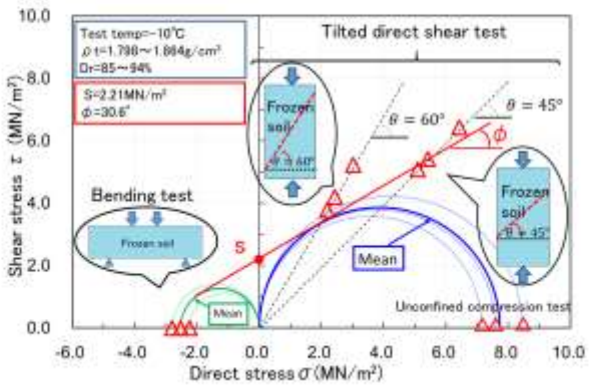

Fig. 3.Typical test results for frozen sandy soil

3.2 Adfreeze strength test

For the adfreeze strength (strip and slip) of the interface between frozen soil and dissimilar materials, a failure criterion line can be obtained using a test method similar to that in (3.1). Note, however, that composite specimens consisting of frozen soil and dissimilar materials are used on which no unconfined compression test can be performed; thus only bending and tilted direct shear tests can be conducted. Bearing in mind as a test example the frozen soil prepared in contact with the steel segments of the shield tunnel as shown in fig. 4, the test results for the adfreeze strength of the interface between frozen soil and steel members are shown in Fig. 5. (no confining frame used). Here again similarly as in Fig. 3, the shear strength increases linearly with the increase in confining pressure. The confining pressure dependency of adfreeze shear strength, which has rarely been considered so far, can be said to provide useful insights for rational design.

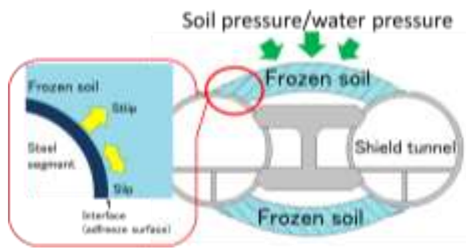

Fig. 4. Typical underground widening work using frozen soil (conceptual image)

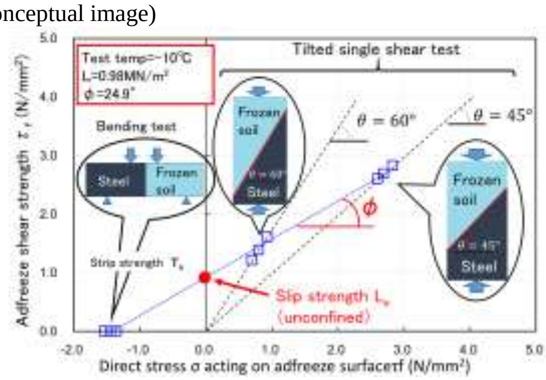

Fig. 5.Typical adfreeze test results (steel-frozen soil)

3.3 Frost heave test

In freezing projects, frost heave testing (Japanese Geotechnical Society, 2009) is conducted for quantitative evaluation of the effects of freeze expansion of cohsive soil and thaw settlement subsequent to termination of freezing. We own frost heave test system that is used the effective vertical loading pressure and the temperature drop rate as parameters to evaluate the frost heave ratio/thaw settlement ratio. In this test, lateral displacements are constrained to allow displacements to occur only in the vertical direction.

The in-situ actual behavior is, however, not only two- or three-dimensional but also a complicated problem involving the consolidation of the surrounding unfrozen soil under freeze expansion pressure. Accordingly, its clarification requires a model experiment. In this case, ground freeze expansion or consolidation has a high dependency on frozen confining pressure and cannot be reproduced in a laboratory model test in which the in-situ confining pressure has no effect. Consequently, there have been few cases of experiments so far. Then, the authors performed a centrifugal model test in an attempt to clarify the behavior.

Fig. 6. shows a typical centrifugal testing model. The ground consists of top and bottom sand layers and a clay layer (frost heave layer) with a plurality of settlement plates placed on the clay layer surface and a plurality of thermocouples placed in the clay layer.

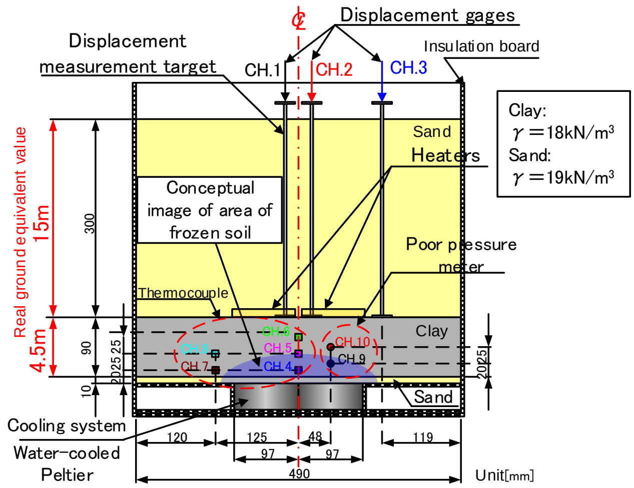

Fig. 6.Experiment model

Freezing was performed using the water-cooled Peltier system placed at the center of the ground bottom to prepare frozen soil from the clay layer bottom edge. Ultimately, circulating water was switched to warm water to raise the surface temperature of the cooling system to thaw the frozen soil. The bottom sand layer was provided as the water supply and drainage layer available for freezing and thawing. The centrifugal acceleration was set to 50 G to perform the experiment so that an earth covering with a depth equivalent to approximately 15 meters in full scale would act on the clay layer. As for the law of similitude for heat conduction in the centrifugal field, with a 1/n model, the temperature gradient will be n times. Therefore, similarly as in seepage phenomena, the elapsed time will be read as $1/n^2$ times of that of the full-size behavior. The heat capacity relevant to sensible and latent heat will, however, be $1/n^3$ times. Hence, a unified similitude will not be achieved. Fig. 7 shows the changes in measurement values over time during the consolidation process (0 to 1.5 hours), the freezing process (1.5 to 7.1 hours), and the thawing process (7.1 to 8.5 hours) from the start time of centrifugal loading until the convergence of clay layer settlement and pore water pressure. (The time axis indicates the test time.) The figure shows how the in-ground temperature gradually dropped during the freezing process because of the cooling from the bottom of the soil chamber. The surface temperature of the Peltier system dropped from the initial temperature of 21°C to 0°C or lower in approximately 1.8 hours and ultimately reached −9.1°C. From the temperature distribution in the ground, it can be determined that the clay layer was frozen to near CH.5 (approximately 30 mm from the surface of the Peltier system). The temporary temperature increases in the Peltier system and CH.4 after approximately 2.2 hours is surmised to have occurred because of the latent heat absorption accompanying ice generation in the ground (phase conversion). According to CH.1 and CH.2, frost heaving started after approximately 3.2 hours. The maximum frost heave amount at the termination of freezing was equivalent to approximately 2.0 cm in full scale. CH.3 distant from the frozen soil experienced little displacement during freezing. It is considered that the water pressure started to rise after the start of freezing because the top unfrozen part was affected by consolidation from the frost heave below the clay layer.

In the thawing process, a major settlement occurred immediately after the start of thawing. Even after the frozen soil completely thawed out, a slow residual settlement occurred. According to CH.1 and CH.2, the maximum settlement amount (displacement that occurred in the period from the beginning to the end of thawing) was equivalent to approximately 5.6 cm in full scale. Thus occurred a settlement amount 2.8 times the frost heave amount. In particular, CH.3, which did not detect frost heave displacement, also detected the occurrence of a major settlement. In actual projects, there are cases where the settlement amount during freezing exceeds the frost heave amount. This can be understood because the settlement occurring only in the vertical direction is more intensive than the frost heaves occurring in the vertical and horizontal directions. According to the results of this experiment, the ratio of the frost heave amount to the thaw settlement amount was 1:3. This result generally agrees with authors' past experience in actual projects. The results of this experiment were applied to the calibration of seepage-thermal deformation coupled analysis capable of predicting complex freeze expansion and significantly contributed to improving analysis reliability.

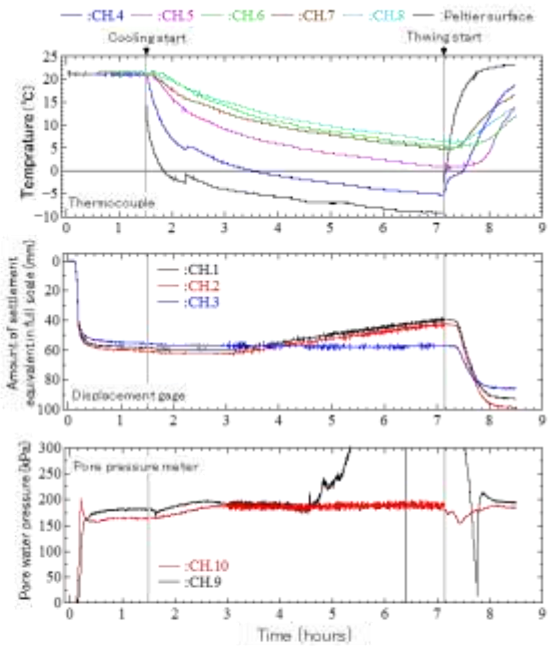

Fig. 7.Experiment results (consolidation-freezing-thawing)

4 CONCLUSION

The main points are as follows:

(1) A quick freezing method and a liquid CO_2 system, both for use at lower temperatures than the conventional method (approximately −30°C), were developed to significantly reduce the time required for frozen soil preparation work.

(2) An LN_2 system suitable for small-scale, short-term freezing projects was used as a means of temporary water cutoff of the sludge draining pipe of the shield machine.

(3) The strengths (unconfined compression, bending tensile, and shear strengths) required for freezing method design can be evaluated using the combination of unconfined compression and bending tests. And the adfreeze strength can be evaluated using the combination of bending and tilted direct shear tests using composite specimens consisting of frozen soil and dissimilar materials.

(4) The model ground was subjected to a freeze test in a centrifugal field to three-dimensionally reproduce the frost-heave behavior of the ground dependent on the confining pressure.

REFERENCES

Japanese Geotechnical Society (2009). Test method for frost heave prediction of soils (JGS 0171).