A study on heat-carrying capacity of brine on development of frozen soil in artificial ground freezing model testing

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ABSTRACT

In this study, the effect of heat-carrying capacity of brine on the growth of frozen soil is examined through an artificial ground freezing model testing, with or without a seepage flow condition. By installing heat flux plates in the model, we can measure the heat flow in soil during the freezing process. The model testing is conducted with different brine temperatures and flow rates, while the number of freezing pipes, density and initial temperature of model soil, and upstream temperature of seepage flow are all kept the same. Preliminary results indicate the brine temperature has a greater effect on the growth of frozen soil than that by the brine flow rate. During the freezing process, the heat flux in soil will vary with time and increase promptly when the temperature drops to or below the freezing point of water, implying sudden surges of heat flow by the phase change of water-to-ice and a higher coefficient of heat conductivity of ice transformed from the water. The observations in model testing are further verified by the associated numerical simulations.

Keywords: brine; heat-carrying capacity; frozen ground; heat flux; model testing; artificial ground freezing (AGF)

1 INTRODUCTION

The objectives of artificial ground freezing (AGF) method in the design and construction of engineering projects are to freeze the ground and to form a frozen wall with high strength and low permeability. In the operation process, the development of frozen ground would be affected by several factors, including the capacity of freezing system, ground temperature, and seepage flow and temperature, which might discount the effectiveness of the AGF method.

The above problems could be eased or prevented by increasing the heat-carrying capacity of brine of the freezing system, or by varying the arrangement of the freezing pipes (Pimentel et al. 2012). Due to direct contact of the freezing pipes with the ground, the heat-carrying capacity of brine through the pipes would be one of the key factors on the formation of the frozen ground. The heat-carrying capacity of brine is related to its temperature and flow rate (Vitel et al. 2015).

In this study, the effect of heat-carrying capacity of brine on the growth of frozen soil is examined through an AGF model testing, with or without a seepage flow condition. By installing heat flux plates in the model, we can measure the heat flow in soil during the freezing process. The model testing is conducted with different brine temperatures and flow rates, while the number of freezing pipes, density and initial temperature of model soil, and upstream temperature of seepage flow are all kept the same.

2 AGF MODEL TESTING

2.1 Test sand and specimen preparation

Ottawa sand (ASTM C778-13 graded sand) is used as the test sand for this study. Physical properties of the sand are as follows: $G_s = 2.60$, $D_{10} = 0.27$ mm, $D_{50} = 0.44$ mm, $C_u = 1.17$, $C_d = 0.9$, $\rho_{dmax} = 1.765$ g/cm^3 and $\rho_{dmin} = 1.550$ g/cm^3. To control density and uniformity, air pluviation is adopted as the method for soil model preparation. At first, the test sand is loaded in a pluviation box with an adjustable opening underneath. By adjusting the opening and height of pluviation box, the density of test sand can be precisely determined. During the pluviation process, the pluviation box is moving back and forth across the model box to obtain a uniform distribution of density in the sand. Based on previous studies (Chang et al. 2013), an opening of 2-mm wide and a falling of 180-cm high are determined to obtain a relative density of 80% for the test sand in this study.

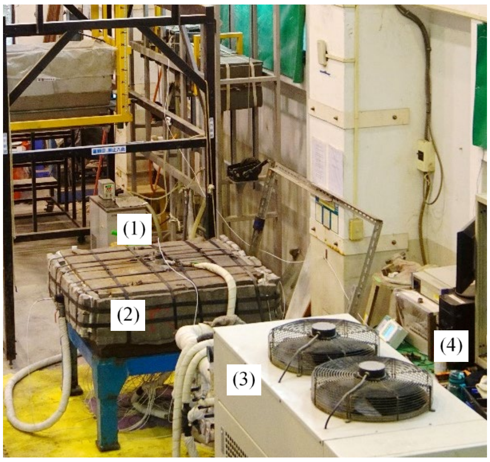
2.2 Saturation procedures

At the completion of pluviation, the upper aluminum plate is put on the model box. To facilitate the saturation process, a 3-cm high block is inserted at the bottom at downstream side of the box, and the water is flowing in slowly from the bottom inlets at the upstream side of the box and exiting to the top outlets at downstream side of the box. As no air bobble comes out of the outlets, a small vacuum of -25 kPa will be applied to the outlets to extract remaining air in the model soil. The vacuum process will last for some period of time until no additional air bobble comes out of the outlets, and the test sand is considered fully saturated for the subsequent tests. Prior to the freezing, an exterior insulation system will be covered on the boundary of the model box.

2.3 Model setup

In this study, an AGF model is fabricated for the investigation of frozen soil development due to seepage flow and freezing pipe arrangement in two dimensions. Fig. 1 shows an overall view of the AGF model setup. The model system includes four parts, Parts (1)~(4), as described below.

Part (1) of Fig. 1 is the water supply system that consists of upper and lower reservoirs connected by water pipelines. Due to head differences, the water will flow into the AGF model for saturation of the test sand and for seepage flow during the testing. Part (2) of Fig. 1 is the AGF model box covered by an exterior insulation with a dimension of approximately 100 cm (L) × 100 cm (W) × 15 cm (H). The model box is designed for two-dimensional (2D) simulations of the artificial ground freeing, where the freezing pipes are installed vertically to the 2D (horizontal) plane and the seepage flows along the 2D (horizontal) plane. Part (3) of Fig. 1 is the freezer for the testing. The brine (calcium chloride solution) is used as the refrigerant of the freezer. The freezing point of brine is controlled by the specific gravity of the solution. Part (4) of Fig. 1 is the data acquisition system for testing. The signals of temperature sensors are collected and saved in a datalogger and then transmitted to a PC for display.



(1) Water supply system (constant temperature)
(2) AGF model box with boundary insulation
(3) Freezer (brine refrigerant)
(4) Data acquisition system

Fig. 1. The AGF model setup over view.

Fig. 2 shows the empty model box with a freezing pipe installed vertically in the model, as well as temperature sensors (resistance thermometers; PT-100) and heat flux plates (HFP01) at the base of the model. The model box is formed by six aluminum alloy plates of 2 cm in thickness. To eliminate potential heat circulation through aluminum plates, insulation sheeting is placed inside the model box to prevent a direct contact of the test sand, as well as in the joints of the aluminum plates. The freezing pipe is made of stainless steel with an outside diameter of 27.3 mm and a wall thickness of 2 mm.

The refrigeration system adopted in this study consists of a freezer and 8 sets of freezing pipelines. The freezer is equipped with a 5-hp compressor and uses brine as the refrigerant that can be cooled down to -34℃. The brine is circulated by a cryogenic pump with a maximum brine flow rate of 0.08 L/sec for a single freezing pipeline in this study. The freezing pipeline is made by braided stainless steel hoses with quick connectors. The brine circulates from the freezer, along the freezing pipelines, through the model box, and then back to the freezer. The measurement system consists of resistance thermometers (PT-100), a datalogger and a personal computer. A total of 66 thermometers are used in this study with a measurement frequency of 1 in every 30 seconds. Figs. 3 & 4 show the arrangemnet of the thermometers and heat flux plates.

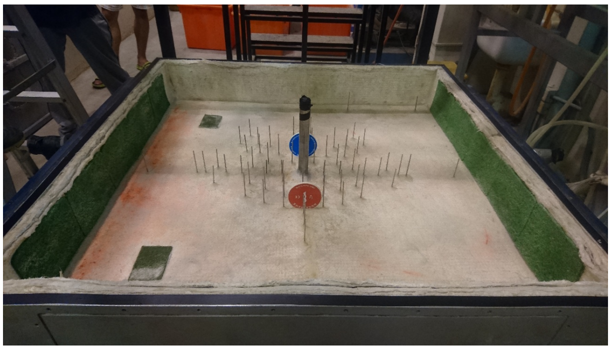


Fig. 2. Model box with a freezing pipe, temperature sensors (PT-100) and heat flux plates.

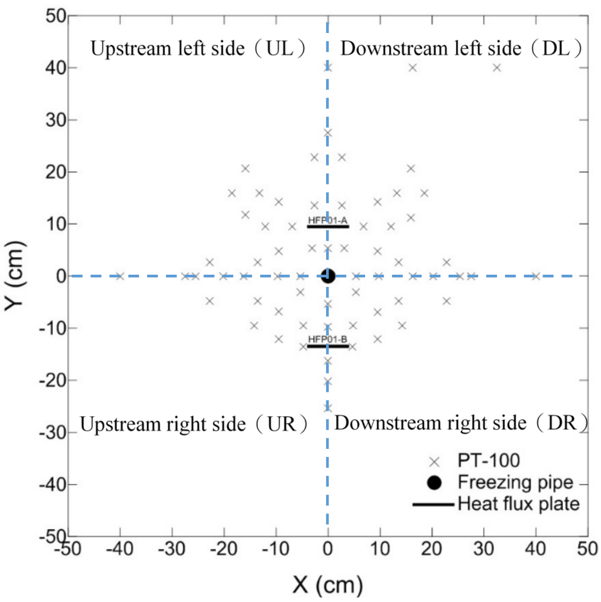


Fig. 3. The arrangement of thermometers and heat flux plates.

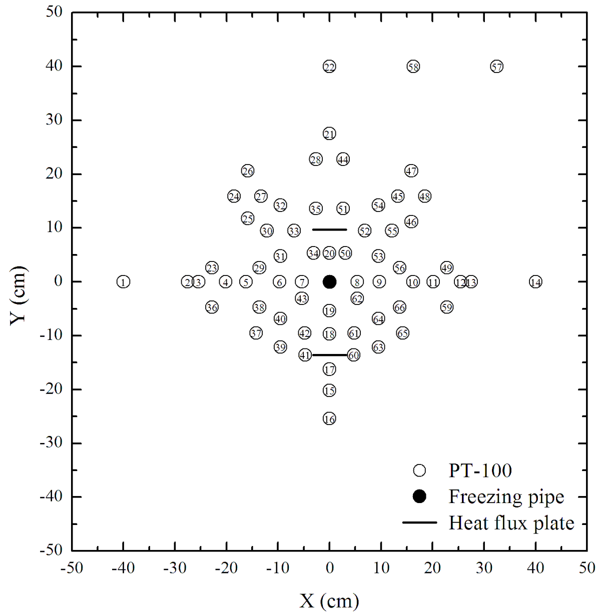


Fig. 4. The numberings of thermometers.

3 PRELIMINARY TEST RESULTS

Fig. 5 shows the development of frozen soil area with respect to different flow rates of brine at various freezing times of concern. We observe the frozen soil area appreciably increases with the increase in the brine flow rate of less than about 0.045 L/sec, and then the frozen soil area becomes stabilized up to a freezing time of 48 hours. The result appears indicating an upper limit of 0.045 L/sec for the brine flow rate in the AGF model testing of this study.

Fig. 6 shows the change in frozen soil area with respect to the brine temperature at various freezing times of concern. As seen in the figure, the frozen soil area continues to grow even if the brine temperature drops to -30℃, with no obvious sign of leveling. The result indicates the brine temperature would have a greater effect on the growth of frozen soil than that by the brine flow rate.

As illustrated in Fig. 7, the heat flux significantly increases in soil during the initial stage of freezing, and then gradually decreases with time. It is noticed that the heat flux will slightly increase due to the phase change of pore water in the process of unfrozen to frozen soil, and then becomes stable as the phase change is complete, a similar result as found by Guo (2011) in the field.

During the freezing process, the heat flux in soil will vary with time and increase promptly when the temperature drops to or below the freezing point of water. The phenomenon implies a sudden surge of heat flow by the phase change of water-to-ice and a higher coefficient of heat conductivity of the ice transformed from the water. This observation in model testing is further verified by the associated numerical simulations.

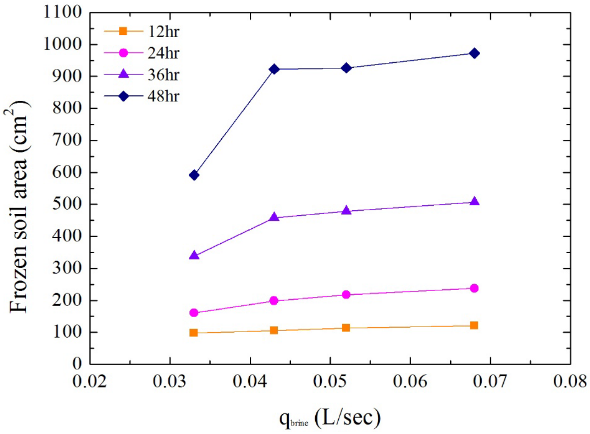


Fig. 5. The growth of frozen soil with different brine flow rates.

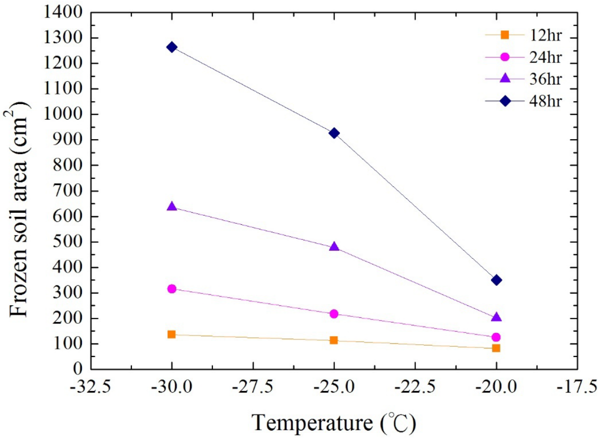


Fig. 6. The growth of frozen soil with different brine temperatures.

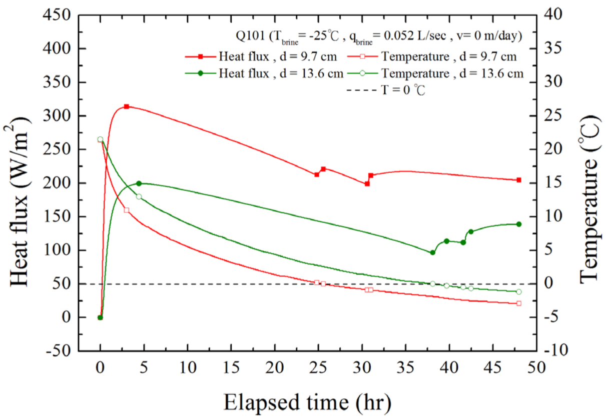


Fig. 7. Development of heat flux and temperature in soil during AGF model test.

4 CONCLUSIONS

The aim of this study is to investigate the influence of heat-carrying capacity of brine on the development of frozen soils during an artificial ground freezing test. Based on physical model testing performed, major findings of the evaluations are listed as follows:

(1) An upper limit of brine flow rate of about 0.045 L/sec is observed for the AGF model of this study, at which the frozen soil area would appear stabi-

lizing without further development in size.

(2) The area of frozen soil will decrease as the brine flow rate is decreasing. Alternatively, the size of frozen soil will grow if the brine temperature is decreasing.

(3) The brine temperature would have a greater effect on the growth of frozen soil than that by the brine flow rate.

(4) The heat flux would significantly increase in soil during the initial stage of freezing, and then gradually decrease with time. It is also noticed that the heat flux will slightly increase due to the phase change of porewater in the process of unfrozen to frozen soil, and then becomes stabilized as the phase change is complete.

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REFERENCES

Chang, C., Chang, M., and Huang, R.-C. (2013). Design of sand pluviation device and its relative density test study. The 15th Conference on Current Researches in Geotechnical Engineering in Taiwan, Yunlin, Taiwan, 1283-1290. (in Chinese)

Guo, D., Yang, M., and Wang, H. (2011). Sensible and latent heat flux response to diurnal variation in soil surface temperature and moisture under different freeze/thaw soil conditions in the seasonal frozen soil region of the central Tibetan Plateau. Environmental Earth Sciences, 63(1), 97-107.

Pimentel, E., Papakonstantinou, S., and Anagnostou, G. (2012). Numerical interpretation of temperature distributions from three ground freezing applications in urban tunneling. Tunnelling and Underground Space Technology, 28(1), 57-69.

Vitel, M., Rouabhi, A., Tijani, M., and Guerin, F., (2015). Modeling heat transfer between a freeze pipe and the surrounding ground during artificial ground freezing activities. Computers and Geotechnics, 63, 99-111.