Heat Transfer Characteristic of Saturated Sand in Steady Flow around a Cooling Pipe

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Abstract

Study presented throughout this paper introduces a laboratory experimental method to observe heat transfer characteristics on the geological material that experiences a cooling process. The experiment combines flow test, cooling process, and observation of temperature change by using infra-red thermograph on saturated Toyoura Sand as the observed heat-transfer medium. Saturated sand is stored in a rectangular container that is connected with water flow and coolant pipe systems while infra-red thermograph camera observing the temperature change on the saturated sand mass. +5.0˚C brine solution is used as the coolant fluid in this experiment so that cooling process could not lead into frozen condition. Thermograph observation results show the obvious temperature change during cooling process. The results also indicate the effect of water flow rate to the heat transfer characteristic. Moreover, flow rate and initial temperature variations are resulted distinctive heat transfer distribution in the sand mass.

Keywords: heat transfer, porous medium, infra-red thermograph, fluid flow

1. Introduction

Natural and artificial cooling of geological material involves thermal, hydrological, and mechanical (THM) processes that may cause considerable change on the geological material itself. Understanding and predicting the behavior of geological material and its groundwater flow under cooling condition is necessary to ensure success and effectiveness of the geological engineering project such as frozen ground wall isolation project, underground LNG storage, tunneling project, ground-coupled heat pump (GCHP) with ground heat exchanger (GHE) technology, etc.

A number of researchers have conducted the substantial study on coupled THM process of geological material by various methods. Many of them focused on the effect of freezing and thawing to the deformation characteristic and deterioration of geological material (Altindag et al., 2004; Chen et al., 2004; Hori & Morihiro, 1998; Yamabe & Neupane, 2001). Besides, numerical analyses have been developed to simulate the coupled THM phenomena (Konrad & Shen, 1996; Neupane & Yamabe, 2001). Another important factor in coupled THM study is the heat transfer itself. Numerical evaluation and laboratory experiment on heat transfer have been conducted to evaluate the variation of soil temperature (Yang et al., 2015) or artificial porous medium (Zhao et al., 2008) around GHE. However, both of those studies were conducted with an assumption of no initial flow occur in the observed or modeled porous material.

Considering the initial flow in heat transfer process is very important since groundwater flow exists in the real field, and even it is very significant in some cases such as Fukushima frozen wall project. Furthermore, visualization of heat distribution that is affected by the initial flow is also important to give comprehensive understanding on coupled THM phenomena. As the first step of continuous study, on this paper, the authors focus on the visual observation of heat distribution of saturated sand in steady flow around a cooling pipe. The experiment was conducted on unfrozen condition so that the main coupled physical phenomena are thermo-hydrological while the mechanical process is not considered.

2. Experimental Setup

Photo. 1 shows the whole experimental system in the present work. It mainly consists of a porous medium specimen that is connected with cooling and water flow systems, circulation systems, also measurement and data acquisition systems. Authors prepare Toyoura sand with 39.5±0.7% average porosity as the porous medium, which is contained inside a rectangular transparent acrylic box (Photo. 2)

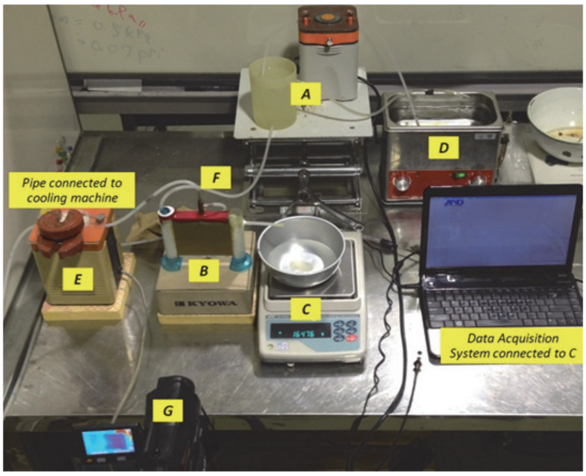

Photo. 1 Experimental system

Inner dimension of the box are 10.50 cm height, 10.80 cm length, and 1.46 cm width. 8.50 cm of the height is filled with sand and the rest 2.00 cm is filled by oil clay as the impermeable layer. The thickness of the acrylic is 1.0 mm with the outer surface directly exposed to the ambient temperature. The box is equipped with an inlet for a water flow system with static-head pressure, and an outlet located at 8.50 cm of box's height. Head pressure is controlled by adjusting the elevation of upstream water storage.

The cooling system consists of RN-N30L cooling machine, circulation pump, connecting pipe and a copper circulation pipe. Cooling machine controls the temperature of Z1 type Nybrine fluid that circulates through a copper pipe, which is inserted into the sand specimen. The copper pipe consists of inner and outer pipe so that brine fluid can be circulated inside the outer pipe. Diameter of inner pipe and outer pipe is 1.0 cm and 0.3 cm, respectively. Three different depths of copper pipe insertion to the sand specimen are prepared in this experiment; (D1) maximum depth down to the base of the box, (D2) 2.0 cm above the base of the box, and (D3) 4.0 cm above the base of the box.

For the measurement system, electric balance is used for flow measurement discharged from the specimen box while infra-red thermograph camera (Testo 876 Thermal Imager) is used for specimen's temperature measurement. It can capture temperature profile of a surface that is focused to sand-filled area (8.50 x 10.80 cm^2).

In this experiment, room temperature is not controlled. Therefore, initial temperature of each experiment might vary to depend on the air temperature and initial temperature of flowing water. There are three phases of experiments; (i) stabilization phase, (ii) cooling phase, and (iii) stop-cooling phase. For the stabilization phase, first, prepared specimen is filled with water and left for about 24 hours to reach saturated condition. In the next day, we install the water flow and cooling system to the specimen. Water flows from upstream storage (A, in Photo. 1) to the sand specimen (B), then it is discharged into outlet storage above the electric balance (C). To produce significant difference between initial temperature and cooling system (+5.0˚C), authors increase the initial temperature of water before it is flowed into sand specimen by using water temperature control apparatus (D). At this phase, cooling system is not circulated yet until the water discharge rate is stable, and the initial temperature condition inside the sand specimen is uniformly distributed. Water continues to flow along the entire experiment phases.

The cooling phase starts when the expected approximate steady-state condition is achieved. +5.0˚C brine fluid with 4.74×10^{-7} m^3/s flow rate is pumped (E) from cooling machine into copper pipe (F) and circulated back so that cooling temperature can be maintained. This phase lasts for 60 minutes. Infra-red thermograph (G) captures the surface temperature profile of the sand specimen in every 1-minute period. The stop-cooling phase starts after 60 minutes of cooling. Brine fluid circulation is stopped while water continues to flow and Infra-red thermograph continues to capture the temperature profile for the next 20 minutes.

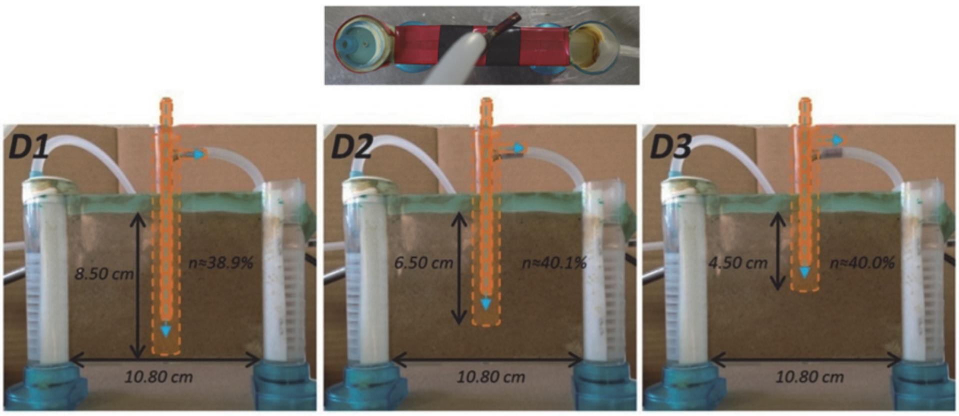

Photo. 2 Sand box specimens

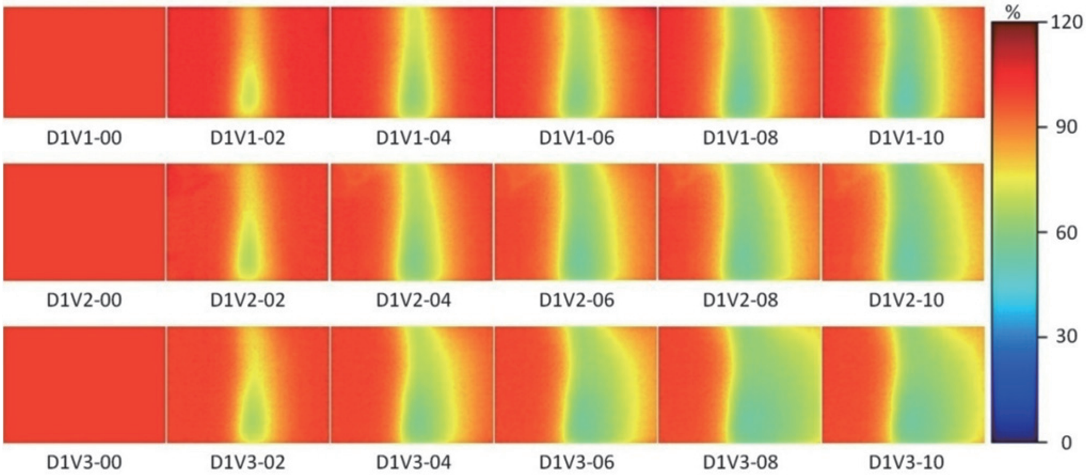

Fig. 1 Heat distribution profile of D1V1, D1V2, and D1V3 (0-10 minutes)

Table 1 Initial condition of each experiment

No.	Exp. Title	Av. Initial T of sand specimen (˚C)	Av. Flow Rate (m^3/s)
1	D1V1	16.3	2.929E-08
	D1V2	15.8	6.874E-08
	D1V3	16.1	1.102E-07
	Average	16.1	-
2a	D1T1	14.7	7.381E-08
	D1T2	15.9	7.339E-08
	Average	-	7.360E-08
2b	D1T3	16.3	2.929E-08
	D1T4	19.2	2.698E-08
	Average	-	2.495E-08
3	D1	16.3	2.929E-08
	D2	15.0	2.921E-08
	D3	16.9	2.688E-08
	Average	16.1	-

In this study, heat transfer distribution is investigated under three experimental variations:

(1) Experiments of D1 specimen with similar initial temperature and different water flow rate
(2) Experiments of D1 specimen with different initial temperature and similar water flow rate
(3) Experiments of D1, D2, & D3 specimens with similar initial temperature and water flow rate

Initial temperature and water flow rate of each experiment are listed on Table 1.

3. Results and Discussion

3.1 Effect of flow rate variation

Figure 1 shows the first 10-minute results of temperature profile of D1V1, D1V2, and D1V3 relative to its initial temperature. Cold temperature spreads from the pipe (median of the box) to its surrounding. Cold-affected area inside the specimen is increasing over the time. The area that has a relative temperature of 75% is shown by yellow color. Within 10 minutes, by focusing to the left side of the cooling pipe (upstream), it can be observed on Figure 2 that D1V3 specimen has less yellow color than D1V1 and D1V2. It means that D1V3 specimen has smaller cold affected area than D1V1 and D1V2. An opposite result can be observed on the right side of the cooling pipe (downstream), D1V3 shows wider cold-affected area while D1V1 shows less. From those series of figures, we can see that flow rate holds an important role in heat distribution characteristic. Water flow hampers heat distribution towards upstream direction while it accelerates heat distribution towards downstream.

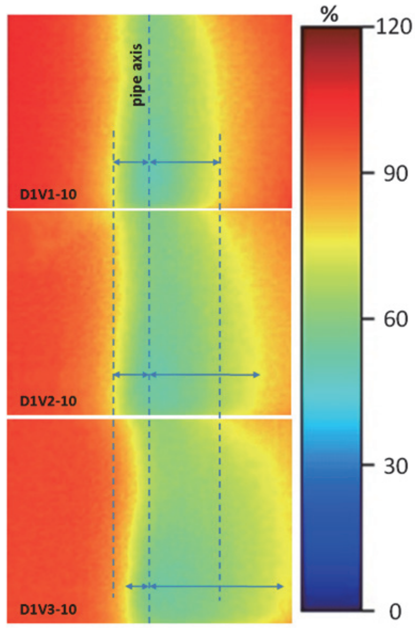

Fig. 2 Comparison of D1V1, D1V2, and D1V3 (at 10 minutes)

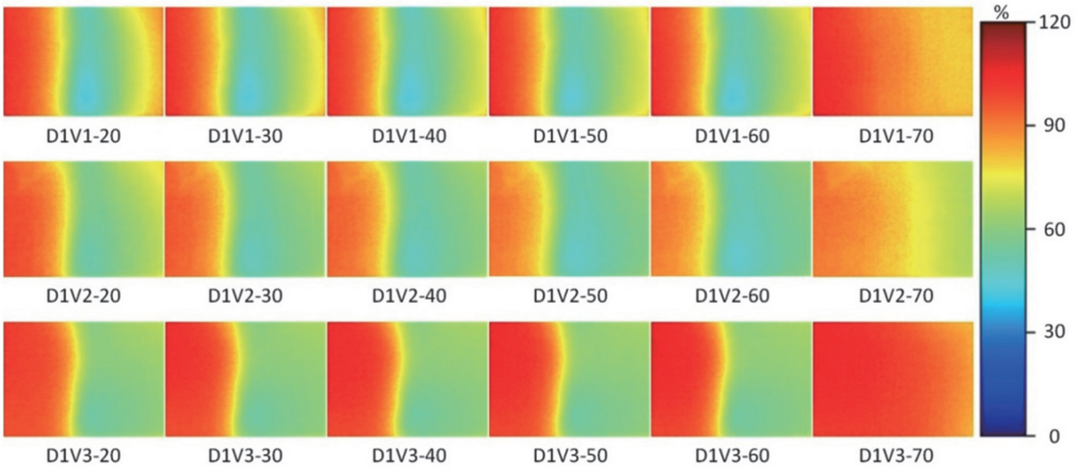

Fig. 3 Heat distribution profile of D1V1, D1V2, and D1V3 (20-70 minutes)

Figure 3 shows the later stage of heat distribution profile up to 70 minutes in 10 minutes interval. By focusing on the pipe location, it can be observed that D1V1 shows more intense dark-blue color than the other two specimens. It indicates that the most significant heat reduction occurs in the sample with low flow rate. The comparison can be seen clearly in Figure 4 where D1V1 is plotted below D1V2 and D1V3. Relative minimum temperature is a percentage of the lowest measured temperature through the specimen's surface proportional to its initial temperature. We can observe that the temperature reaches quasi-steady-state after 10-15 minutes of cooling. Quasi-steady-state conditions of D1V1, D1V2, and D1V3 are reached at 41%, 47%, and 52% of initial temperature, respectively. Specimen with higher flow rate reaches the minimum temperature earlier that the lower flow rate specimen.

Besides, D1V2 specimen shows different characteristics during the stop-cooling phase. Increase in temperature that occurs in D1V2 after the cooling was stopped is slower than the others, which is indicated by lighter color (Fig. 3 D1V2-70) and lower line (Fig.4). This distinction is most likely caused by the temperature changes of water inside upstream storage, which is controlled manually against room temperature and water replenishment. Therefore, change is likely to occur during the experiment.

From these experiments, we can say that heat transfer in saturated porous media is mainly governed by the heat convection process, which is significantly affected by the movement of the fluid. Water flow prevents cold temperature to be accumulated at static point and accelerates heat convection to the wider area.

3.2 Effect of initial temperature variation

Figure 5 shows the relative minimum temperature over time of D1 specimen in different initial temperature condition. D1T1 and D1T2 have higher discharged water flow rate with the average value of 7.360×10^{-8} m^3/s than D1T3 and D1T4 with average value of 2.495×10^{-8} m^3/s. Despite the graph shows two groups of flow rate, the effect of initial temperature on each experiment is clearly distinguished. It can be observed that specimen with higher initial temperature experiences more significant temperature

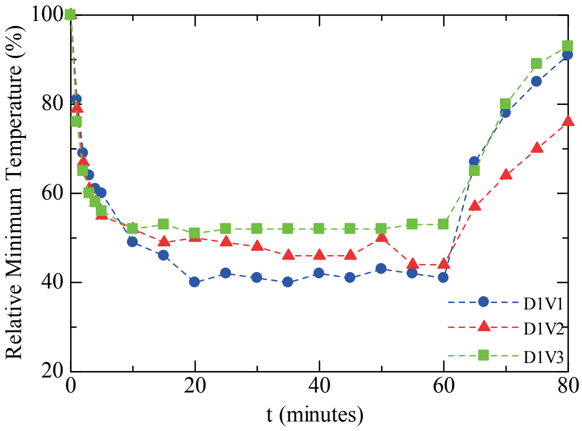

Fig. 4 Relative minimum temperature by time of D1 in different flow rate

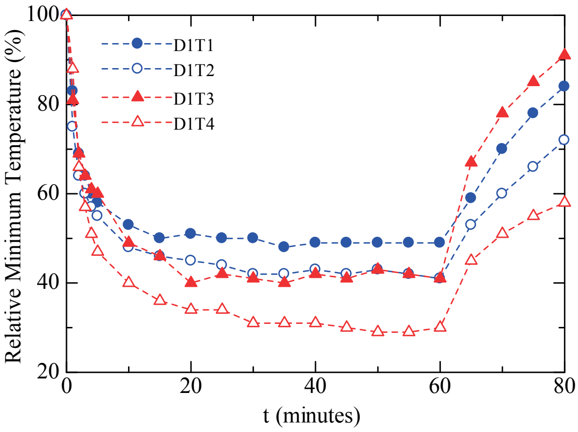

Fig. 5 Relative minimum temperature by time of D1 in different initial temperature

reduction. D1T4 that has the highest initial temperature experienced the largest decline. Its minimum temperature reached 29% of the initial. Otherwise, the lowest temperature of D1T1 only reached 49% of the initial. For other two specimens that have more similar initial temperature condition, their relative minimum temperatures are also close; 41% for D1T2 and 40% for D1T3.

In case of flow rate variation, Figure 5 also supports the previous discussion of Figure 4, which found that specimen with higher flow rate reaches the minimum temperature earlier that the lower flow rate specimen. By the combination of high flow rate and low initial temperature, D1T1 and D1T2 reach quasi-steady-state in 10 to 15 minutes after cooling started. In contrast, D1T3 and D1T4 which have lower flow rate and higher initial temperature reach quasi-steady-state after 20 to 25 minutes of cooling.

Results of this experiment are in accordance with the basic principle of heat transfer. Higher initial temperature means significant thermodynamic potential, which resulting more energy requirements to reach equilibrium condition.

3.3 Effect of pipe's depth variation

Figure 6 shows the first 10-minute results of relative heat distribution of D1, D2, and D3, respectively. We can clearly distinguish the difference of pipe's depth at the beginning of the cooling process. Since cooling pipe of D1 specimen is buried down to the base of the box, significant heat transfer mainly occurs along the horizontal axis. In contrast, D2 and D3 specimens show more radial movement of heat changes. In both D2 and D3, significant temperature changes on the early stage (first 2 minutes) can only be seen in the area as long as the depth of pipe. Subsequently, temperature changes within the area below the pipe are more obvious after 4 minutes of cooling and tend to spread in all directions during cooling. Besides, we can also observe the effect of water flow; right side of the pipe shows lighter color than the left side. Basically, heat distributes in all directions, but 2.844×10^{-5} m^3/s average flow of water from the right to left has produced the heat distribution tendency towards downstream.

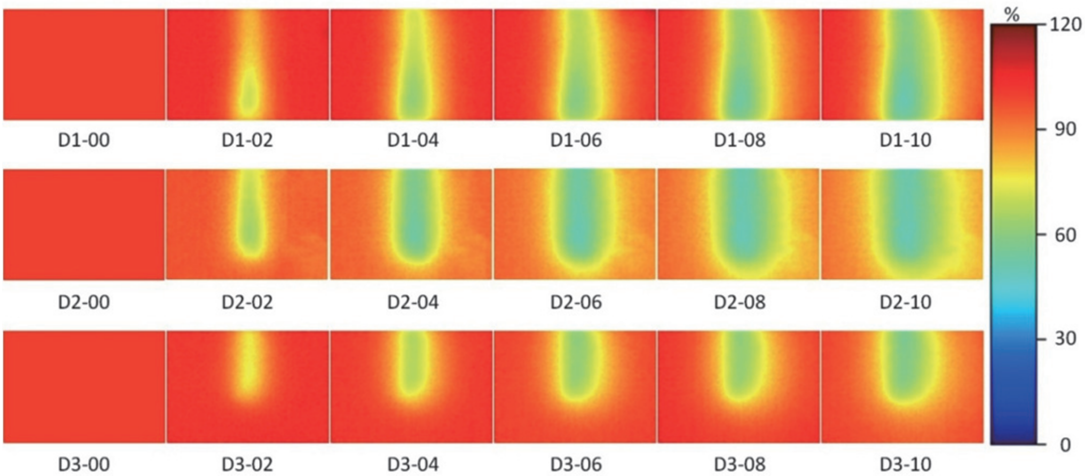

Fig. 6 Heat distribution profile of D1, D2, and D3 (0-10 minutes)

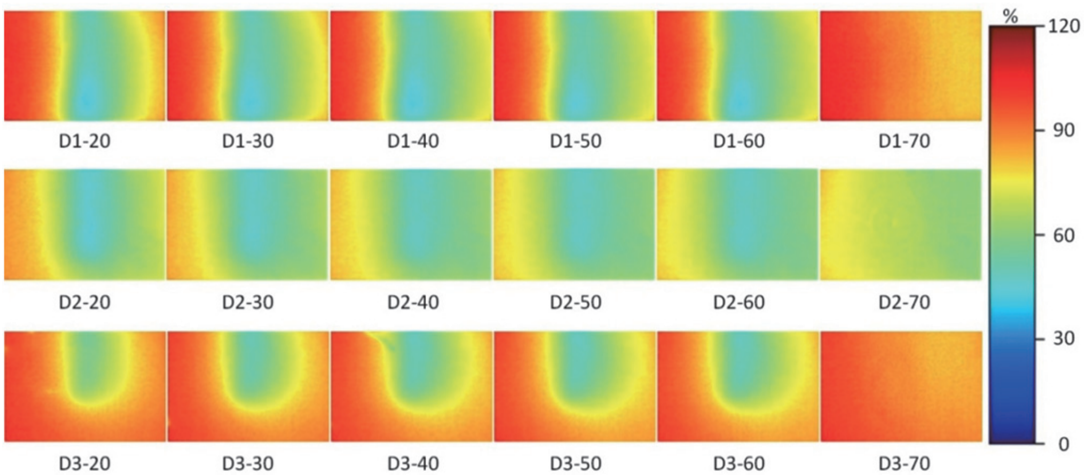

Fig. 7 Heat distribution profile of D1, D2, and D3 (20-70 minutes)

Figure 7 shows the later stage of heat distribution profile up to 70 minutes in 10 minutes interval. Change of temperature occurred in D2 is greater than D1 and D3. A possible reason for this difference is caused by the heterogeneity of room and flowing water temperature. In addition to the initial temperature difference of the specimens, room temperature is also varied over the time. During the experiment, room temperature of D2 specimen was 6˚C, while D1 and D3 were 10˚C and 8˚C respectively. That low room temperature may affect temperature of flowing water and accelerate the cooling process of D2 specimen. However, it is still unclear and has to be proven by further investigation.

As previously discussed, direction of heat convection depends on the fluid flow. Change of temperature on vertical axis to the bottom part of D2 and D3 pipes occurs even though the main flow direction is horizontal. It may be caused by the differences in water density. Water with lower temperature but not less than 4˚C has higher density so that it tends to move downward due to gravity. Moreover, heat convection is not the only mechanism governing the heat transfer in saturated porous media. Heat conduction process may also occur due to contact of each sand and water molecules.

4. Conclusion

In this study, we introduced a laboratory experimental method on the saturated sand in steady flow at around a cooling pipe. This method is effective to observe the heat transfer and able to distinguish the heat transfer characteristic based on each determining factor; flow rate variation, average initial temperature variation and pipe's depth variation. From the experimental results, the following conclusions can be obtained:

- Heat transfer through the sand mass is mainly governed by thermal convection of flowing water.
- Both maximum temperature reduction and required cooling duration before quasi-steady-state condition are decreasing with the increasing flow rate.
- Initial temperature affects the required cooling duration to reach quasi-steady-state condition; higher initial temperature requires longer cooling duration.
- Depth of pipe plays the important role in the heat distribution and effectiveness of cooling process.

The results obtained in this experiment are not sufficient to explain a frozen ground case since it may have different behavior, especially on how the ice formation affects water flow. Besides, the effect of flow velocity through the formation of a frozen body is necessary to be investigated. However, as the beginning of continuous study, these results provide clear evidence on the heat transfer behavior around a cooling pipe. Therefore, further experiment is required to observe the heat transfer characteristic of saturated sand in steady flow at around a freezing pipe.

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References

Altindag, R., Alyildiz, I. S., and Onargan, T. (2004): Mechanical property degradation of ignimbrite subjected to recurrent freeze-thaw cycles, International Journal of Rock Mechanic and Mining Sciences, Vol. 41, pp. 1023-1028

Chen, T. C., Yeung, M. R., and Mori, N. (2004): Effect of water saturation on deterioration of welded tuff due to freeze-thaw action, Cold Regions Science and Technology, Vol. 38, pp. 127-136

Hori, M. and Morihiro, H. (1998): Micromechanical analysis on deterioration due to freezing and thawing in porous brittle materials, International Journal of Engineering Science, Vol. 36, No. 4, pp. 511-522

Konrad, J. M., and Shen, M. (1996): 2-D frost action modeling using the segregation potential of soils, Cold Regions Science and Technology, Vol. 24, pp. 263-278

Neupane, K. and Yamabe, T. (2001): A fully coupled thermo-hydro-mechanical nonlinear model for frozen medium, Computers and Geotechnics, Vol. 28, pp. 613-637

Yamabe, T. and Neupane, K. (2001): Determination of some thermo-mechanical properties of Shirahama sandstone under subzero temperature condition, International Journal of Rock Mechanic and Mining Sciences, Vol. 38, pp. 1029-1034

Yang, W., Kong, L., and Chen, Y. (2015): Numerical evaluation on the effects of soil freezing on underground temperature variations of soil around ground heat exchangers, Applied Thermal Engineering, Vol. 75, pp. 259-269

Zhao, J., Wang, H., Li, X., and Dai, C. (2008): Experimental investigation and theoretical model of heat transfer of saturated soil around coaxial ground coupled heat exchanger, Applied Thermal Engineering, Vol. 28, pp. 116-125