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Estimation of the amount of refrigerant in artificial ground freezing for subsea tunnel

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ABSTRACT

Subsea tunnel can be vulnerable to seawater intrusion caused by unpredictable high-water pressure during construction. A novel technique of artificial ground freezing will be a promising alternative to conventional reinforcement or water-tightening technology.

In this study, the freezing energy and time requirement was calculated by the theoretical model of the heat flow to estimate the total amount of refrigerant required for applying the artificial ground freezing (AGF). Then, its validity was evaluated by comparing the results between the freezing chamber experiment and the numerical analysis. In particular, the freezing time showed no significant difference between the theoretical model and the numerical analysis. The amount of refrigerant for artificial ground freezing was estimated from the numerical analysis and the freezing efficiency obtained from the chamber test. In addition, the energy ratio for maintaining frozen status was calculated by the proposed formula.

1. INTRODUCTION

Subsea tunnels are essential for long-distance railway, which is less influenced by pollutants and weather conditions, and it is very economical. Subsea tunnels, unlike a typical land tunnel, are vulnerable to seawater intrusion caused by unpredictable high-water pressure during construction. Thus, there is a demand for ground improvement overcoming such a risky condition. The artificial ground freezing (AGF) can be applied regardless of the ground conditions. Brine and liquid nitrogen are mainly used as a refrigerant in the AGF. Liquid nitrogen with the low boiling point is suitable as a refrigerant under high water pressure with salinity. But, in enclosed environment such as a long-span subsea tunnel, there is a disadvantage that the evaporated nitrogen gas after heat exchange may suffocate the workers. To develop the AGF considering the characteristics of subsea tunneling such as high-water pressure and enclosed environment, liquid air mixed of liquid nitrogen and liquid oxygen is proposed as a freezing refrigerant. The liquid air is almost identical to the composition of air in atmosphere after evaporation.

A theoretical model of heat flow for a single freeze pipe and freeze wall was developed to compute the energy and time required for freezing and maintaining frozen status. Then, its validity was evaluated by comparing the results between the freezing chamber experiment and the numerical analysis. In addition, the energy ratio for maintaining frozen status was calculated by the proposed formula.

2. Refrigerants characteristics

2.1 Brine

The brine has advantages of the reuse of refrigerant, which can reduce the cost along with low toxicity and low risk to workers. But, the brine has disadvantages that it takes a relatively long freezing time and the more complex refrigeration plant is required.

2.2 Liquid nitrogen

The liquid nitrogen applied by simple facilities has advantages of quick freezing time due to the lower boiling temperature than brine. But, there are disadvantages that the reuse of refrigerant is impractical, and the evaporated nitrogen gas after the freezing process may inevitably suffocate the workers in enclosed environment.

2.3 Liquid air

Rapid ground reinforcement and water proof can minimize unpredictable damage to a tunnel due to seawater intrusion and ground deformation. For the rapid AGF under high water pressure, liquid nitrogen is suitable. However, there is a major concern about the evaporated nitrogen gas after heat exchange in enclosed environment.

In order to mitigate these problems, a new refrigerant capable of rapid freezing under high-water pressure in the subsea tunnel condition is proposed. Liquid air consisting of liquid nitrogen and liquid oxygen is introduced as a novel refrigerant capable of rapid freezing and reducing the risk of suffocation for application to subsea tunnels. The liquid air is almost identical to the composition of air in atmosphere after evaporation, so there is no concern about the operator's suffocation, and the low boiling point (-194.5℃) is not much different from the liquid nitrogen (-195.8℃). Table 1 summarizes the characteristics of refrigerants.

Table 1. Characteristics of refrigerants (from Stoss and Valk (1979))

	Brine	Liquid nitrogen	Liquid air
minimum temperature	-55~-34℃*	-195.8℃*	-194.5℃*
application section	open and enclosed	open space	open and enclosed
reuse of coolant	standard	impracticable	impracticable
frost penetration	slow	fast	fast
toxicity	small	required ventilation	none
refrigeration plant	required	not required	not required

* theoretical

3. Theoretical model of heat flow

Fig. 1 shows 2-dimensional radial heat flow of single freezing tube for steady state condition. Total heat energy for freezing the radius R consists of [1] latent heat of freezing zone, [2] Sensible heat in the frozen area by temperature difference of freezing point of water with the surrounding ground, [3] sensible heat in the frozen area by temperature difference of freezing point of water with the cooled temperature and [4] sensible heat released to the unfrozen ground. Total heat energy is given by Eq. (1), and Eq. (1) can be summarized as Eq. (2). Freezing time is calculated as Eq. (3). Eq. (4) shows the result of [4] in Eq. (1). Eq. (4) is sensible heat released to the unfrozen ground and can calculate heat energy required to maintain freezing.

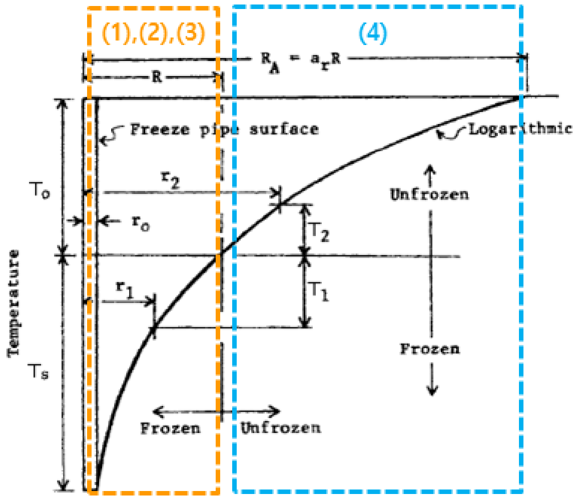

Fig. 1. Temperature distribution curve according to distance of single freezing tube (Andersland et al., 2004)

0

$$\mathbf{Q_I} = \pi R^2 L + \pi R^2 C_u T_0 + C_u T_0 \frac{2\pi C_f T_s}{\ln \frac{\boldsymbol{R}}{\mathbf{r_0}}} \int_{\mathrm{r_0}}^{R} \mathbf{r_1} \ln \frac{\boldsymbol{R}}{\mathbf{r_1}} d\mathbf{r_1} + 2 C_u T_0 \int_{R}^{\mathrm{a_r} R} \left(\mathbf{1} - \frac{\ln \mathbf{r_2}/\boldsymbol{R}}{\ln \mathbf{a_r}} \right) \mathbf{r_2}\, d\mathbf{r_2}$$

$$= [1] + [2] + [3] + [4] \tag{1}$$

$$\mathbf{Q_I} = \pi R^2 \left(L + \frac{\mathrm{a_r}^2 - 1}{2 \ln \mathrm{a_r}} C_u T_0 + \frac{C_f T_s}{2 \ln \frac{\boldsymbol{R}}{\mathrm{r_0}}} \right) \tag{2}$$

$$\mathbf{t_I} = \frac{R^2 L_I}{4 k_f T_s} \left(2 \ln \frac{\boldsymbol{R}}{\mathrm{r_0}} - 1 + \frac{C_f T_s}{L_I} \right) \tag{3}$$

$$\mathbf{Q_{I[4]}} = \pi R^2 C_u T_0 \left(\frac{\mathrm{a_r}^2 - 1}{2 \ln \mathrm{a_r}} - 1 \right) \tag{4}$$

4. Freezing time and refrigerant consumption

In order to evaluate theoretical model, a lab-scale freezing chamber was devised to measure the freezing rate and the temperature change in the soil specimen. The freezing time and the amount of the refrigerant consumed were determined according to the salinity and the refrigerant types.

4.1 Lab-scale freezing chamber experiments

In the lab-scale freezing chamber experiment, the artificial silica sand No. 6 was used to minimize the compaction effect during specimen preparation in the chamber. The freezing pipe was shaped in double-tube made of stainless steel. When the refrigerants were injected through the inner tube, it was evaporated at the bottom and discharged to the atmosphere through the outer space. Four thermocouples were installed at the interval of 51 mm in the horizontal direction, so that the temperature with time could be measured at the designated locations. The consumption of refrigerant was automatically recorded with weight of the LGC. Additional thermocouples were installed in the inlet and outlet of the bypass pipe to measure the temperature of the refrigerant and the freezing pipe. Fig. 2 is the overview of the real experimental system.

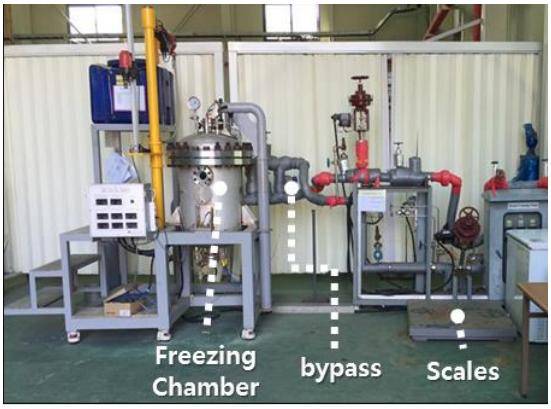

Fig. 2. Picture of lab-scale freezing chamber experiment

Table 2 summarizes salinity conditions (salinity = 0‰ and 35‰) and refrigerant types (liquid nitrogen and liquid air).

Table 2. Cases of experiment with salinity and refrigerant types

		Liquid Nitrogen		Liquid Air	
Cases		Case 1	Case 2	Case 3	Case 4
Salinity		0‰	35‰	0‰	35‰
Temperature	in chamber	16.0℃	17.9℃	7.1℃	5.5℃
	in lab	16.1℃	17.9℃	4.5℃	4.5℃
Date		Apr. 23, 2015	May 13, 2015	Dec. 24, 2015	Dec. 22, 2015

In Case 1 and 3, the experiments were terminated when the temperature recorded at the fourth thermocouple reached 0℃. In Case 2 and 4, the experiments were terminated when the temperature became -1.91℃ with consideration of freezing point reduction by salinity. Table 3 summarizes the freezing time and refrigerant consumption.

Table 3. Results of experiment

	Liquid Nitrogen		Liquid Air	
Cases	Case 1	Case 2	Case 3	Case 4
Consumption(kg)	397.3	381.2	426.5	364.7
Freezing time(sec)	33,749	32,180	21,172	17,892
Freezing point (℃)	0	-1.91	0	-1.91

The overall freezing time was longer for liquid nitrogen (Case 1, 2) than for liquid air (Case 3, 4). This is attributable to temperature difference during the laboratory experiments (about 10℃ in Table 2).

4.2 Theoretical model

Table 4 summarizes the freezing time and refrigerant consumption of theoretical model.

Table 4. Results of theoretical model

	Liquid Nitrogen		Liquid Air		Remarks
Cases	Case 1	Case 2	Case 3	Case 4	
Amount of energy (J/m)	60,435,226	66,491,140	45,338,458	45,779,019	Eq. (2)
Freezing time (sec)	28,162	26,310	22,670	19.492	Eq. (3)
Heat of vaporization (J/mol)	5,570		5,820		*
Molecular weight (g/mol)	28.0134		28.8105		
Amount of refrigerant (kgf)	39.395	33.441	22.827	23.024	**

* Handbook of chemistry and physics (2004)
** Latent heat only

4.3 Numerical analysis

An FE analysis was performed to numerically simulate the freezing chamber experiment. COMSOL Multiphysics was employed in the FE analysis. In order to simulate the heat transfer process by freezing, the time-dependent analysis was performed considering the phase change in the heat transfer module in the solid state. The values of heat capacity for saturated and frozen samples were calculated based on the specific heat values of water, ice, and silica as 2,090, 4,182 and 830 J/kg.℃, respectively.

Table 5 summarizes the freezing time and refrigerant consumption of numerical analysis. Fig. 3 shows the freezing energy calculated from the numerical analysis. By integrating this energy, the total amount of energy required for freezing can be calculated.

Table 5. Results of numerical analysis

	Liquid Nitrogen		Liquid Air		Remarks
Cases	Case 1	Case 2	Case 3	Case 4	
Amount of energy (J/m)	105,213,514	111,877,231	79,104,391	79,757,937	
Freezing time (sec)	29,560	26,880	23,320	20,110	
Amount of refrigerant (kgf)	57.453	61.092	42.517	42.868	*

* Latent heat only

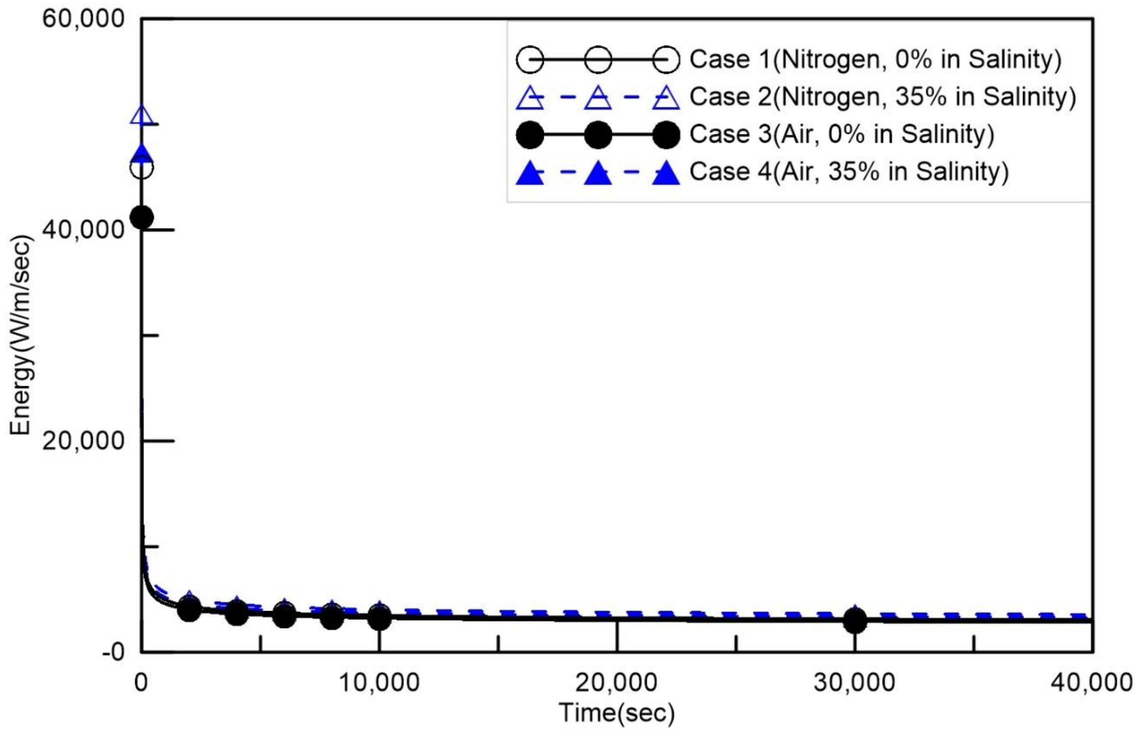

Fig. 3. Freezing energy with time in numerical analysis

5. Evaluation

5.1 Evaluation of freezing time

Fig. 4 compares freezing time from experiments, theoretical models, and numerical analysis. The freezing time shows no significant difference between the theoretical model and the numerical analysis even though the freezing time of the theoretical models is rather short. This is because numerical analysis can simulate the formation of freezing bulbs (changes of thermal conductivity of saturated soil and freezing soil) over time, but the theoretical model is the result of substituting simplified thermal conductivity.

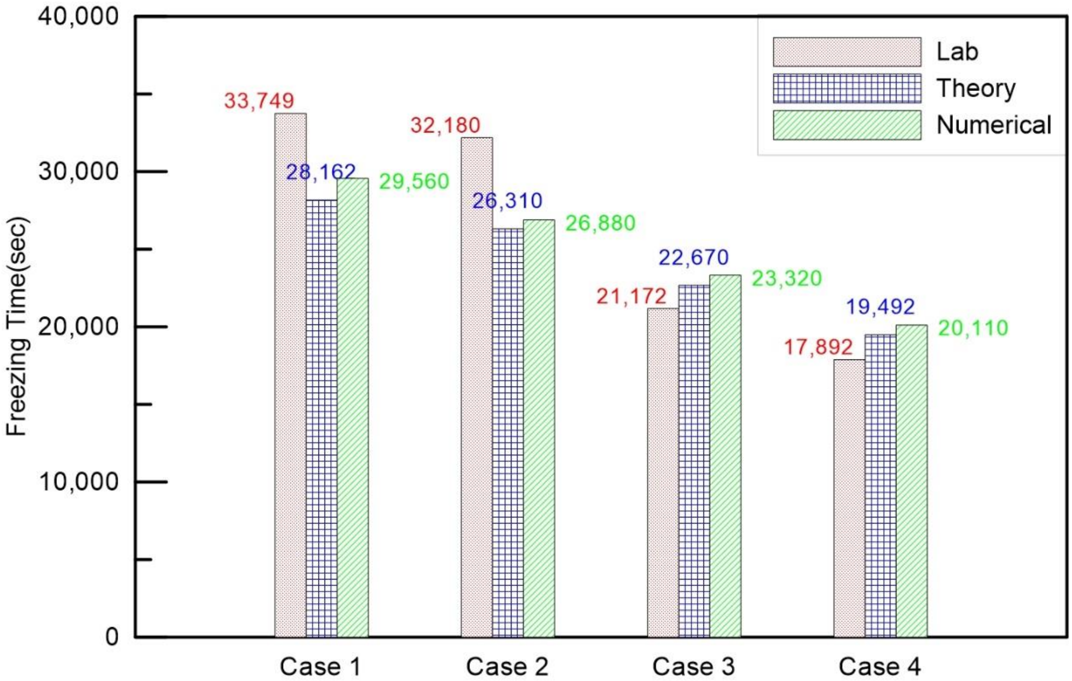

Fig. 4. Freezing time from experimental, theoretical model and numerical analysis

5.2 Evaluation of freezing efficiency

The freezing efficiency is obtained as the theoretical quantity of refrigerant calculated from the numerical analysis divided by that actually consumed in the lab-scale freezing chamber experiment. In the experiment, the consumption of refrigerant was estimated by measuring the weight change of the LGC with time (Table 3). The total amount of freezing energy of liquid air (with the boiling point of -183.0℃) is slightly smaller than that of liquid nitrogen (with the boiling point of -194.0℃) due to the difference in the boiling point.

Considering that the temperature difference before and after passing through the freezing pipe is not large, the latent heat of the refrigerant is considered as the total amount of freezing energy of the ground.

Liquid air was injected at a flow rate more than twice greater than liquid nitrogen. Therefore, the freezing efficiency of liquid air (10.9% on average) is smaller than liquid nitrogen (15.2%). Also, the results of freezing efficiency reflect the limitation of laboratory experiments, in which the length of freezing pipe is not long enough.

Table 6. Calculation of freezing efficiency in lab-scale freezing chamber

	Liquid Nitrogen		Liquid Air		Remarks
Cases	Case 1	Case 2	Case 3	Case 4	
Amount of energy (J/m)	105,213,514	111,877,231	79,104,391	79,757,937	Numerical analysis
Amount of refrigerant (kgf)	57.453	61.092	42.517	42.868	Latent heat only
Consumption(kg)	397.3	381.2	426.5	364.7	experimental
Freezing efficiency (%)	14.461	16.026	9.969	11.754	

5.3 Evaluation of freezing energy ratio

Table 7 shows energy ratio for maintaining frozen status. In the case of liquefied nitrogen (Case 1, 2), the energy ratio for freezing was 33.0% on the average, and for liquefied air (Case 5, 6) it was 18.8% on average. The difference was very large. This is attributable to temperature difference during the laboratory experiments (about 10℃ in Table 2).

Table 7. Energy ratio for maintaining frozen status

	Liquid Nitrogen		Liquid Air		Remarks
Cases	Case 1	Case 2	Case 3	Case 4	
Amount of energy (J/m)	60,435,226	66,491,140	45,338,458	45,779,019	Eq. (2)
Amount of energy for frozen status (J/m)	18,785,587	23,258,905	8,336,104	8,700,075	Eq. (4)
Energy ratio(%)	31.08	34,98	18.36	19.01	Eq. (4)/Eq. (2)

6. CONCLUSIONS

In order to evaluate a theoretical model, a lab-scale freezing chamber was devised to measure the freezing rate and the temperature change in the soil specimen. The freezing time and the amount of the refrigerant consumed were determined according to the salinity and the refrigerant types. The findings and conclusions are summarized as followings:

1. The freezing time shows no significant difference between the theoretical model and the numerical analysis even though the freezing time of the theoretical models is rather short.

2. The freezing efficiency of liquid air was 10.9% on average, and for liquid nitrogen it was 15.2%. This reflects the limitation of the laboratory experiments, in which the length of freezing pipe is not long enough.

3. When the temperature of interface was high, the ratio of energy for freezing was calculated as 33.0% (average temperature 17 ℃) and 18.8% (average 6 ℃) in case of low temperature of interface. It is believed that it will depend on the depth of rock cover in the subsea tunnels and the water temperature on the sea floor.

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