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Effect of Freezing Saturated Sandy Soil under Undrained Condition on a Buried Steel Pipe

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Abstract

Buried water pipe is exposed to excessive ground stress resulting from ground freezing and thawing in low temperature of winter which might lead to the rupture or deformation of water pipe. This paper is intended to identify, through a full scale model test, the ground temperature variation around the buried pipe depending on variation of ambient temperature as well as the displacement of the buried pipe and the stress behavior, and consequently, stress concentration and frost heaving were observed around buried pipe when ground was frozen. And despite of using sandy soil which is considered non-frost susceptible material for the test, frost heaving was occurred depending on water content and drainage condition. Viewing such result, even in case of displacing bedding and backfill material with non-frost heaving material, the countermeasure to protect from frost heaving is necessary depending on surrounding drainage condition, groundwater level and water contents.

***Keywords**: Frost heaving, Frost susceptibility, Buried pipe, Backfill, Drainage*

1. Introduction

Recently intensity and duration time of cold wave in winter tends to increase which leads to increase in frost penetration depth and the risk of rupture of buried water pipe due to expansion by ground freezing or differential settlement caused by thawing in spring. In Korea where the temperature varies above or below zero seasonally, ground tends to expand at low temperature due to freezing which results in irregular heaving and excessive stress on certain part of buried pipe and eventually the rupture of the structure (Sellmann, 1989) The techniques for predicting ground expansion caused by freezing were proposed in many studies (Kim *et. al.*, 2010; Kang *et. al.*, 2013) but the study to identify the stress behavior of buried pipe through a full-scale test has been far behind.

To prevent the risk of rupture of water pipe, the studies proposing the method to displace frost-susceptible soil with gravel or rubble which is considered non-frost susceptible (Kang *et. al.*, 2009) and the method using waste tire or vinyl (Gandahl, 1985) were conducted. US Army Corps of Engineers proposed the classification method to determine the frost susceptibility of soil in a bid to prevent the damage by frost heaving and even in case of using sandy soil or gravel with larger particle size, it requires identifying the frost susceptibility of the ground through lab test (US Army TM 5-818-2-2, 1985) Then according to current domestic standard specifying the design and installation method of water pipe (Waterworks Facilities Standard, 2004; Road Construction Standard Specification, 2009; Civil Engineering Works Standard Specification, 2005), water pipe shall be buried simply deeper than frost penetration depth which was determined based on maximum frost penetration depth distribution (Contour

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Map) calculated according to the data measured nationwide during 1980~1989 by National Construction Laboratory Institute, without incorporating such grounding freezing phenomenon as granular powder content, surrounding drainage, groundwater level and water contents.

Moser(1990) demonstrated that the maximum load on buried pipe when ground is frozen might increase twice the load at unfrozen condition and recommended the depth to be 30~60cm below the frost line. Canadian water pipe design Guidelines(2004) indicates frost penetration depth is determined depending on various factors including soil type, water content, snow cover, snow pack and freezing index and pipe depth is affected by wet areas and thus the depth needs to be determined referring to successful similar cases, instead of design calculation.

For a full-scale model test conducted in this paper, 50mm diameter and 3mm-thick corrosion-resistant stainless steel (STKM500) was used and Jumunjin sand which is considered non-frost susceptible material was used as backfill material to make it similar with actual condition, referring to domestic pipe installation standard. To identify the occurrence of frost heaving depending on ground saturation and drainage condition despite of installation in compliance with current standard, effect on buried pipe was monitored under undrained condition at below zero temperature after saturating the specimen. Model test was conducted at large chamber and to maintain the temperature for test purpose, chamber was installed in freezing chamber separately.

2. Frost Heaving Test of Saturated Non-Frost Susceptibility

2.1. Specimen

When burying water pipe, the depth is determined based on maximum frost penetration depth or the threshold for ground freezing and non-frost susceptible material is used as backfill material. Sandy soil which is considered stable against frost heaving is generally used domestically.

Sandy soil has a larger particle spacing and thus has less effect by frost heaving by capillary phenomenon but still has a risk of frost heaving when contains granular power more than a certain level. Table 1 shows the possibility of frost heaving in even gravel or sandy soil defined to determine frost susceptibility according to COE’s soil classification, depending on granular powder contents and in case of ground containing high granular powder contents, separate lab test shall be carried out to determine the frost susceptibility. Granular powder according to COE’s criteria refers to soil containing the particles sized less than 0.02mm and the contents in weight percentage shall be considered.

Table 1. Soil Classification for Frost Heave Susceptibility (US Army TM 5-818-2-2, 1985)

Frost heave susceptibility	*Soil type*	*Granular powder content(%)*	*Unified soil classification*
NFS	Gravels, Crushed stone, Rock	0-1.5	GW, GP
	Sands	0-3	SW, SP
PFS	Gravels, Crushed stone, Rock	1.5-3	GW, GP
	Sands	3-10	SW, SP

NFS : Non Frost Susceptible
PFS : Possible Frost Susceptible, but required laboratory test to determine frost design soils classification

In this paper, even in case of using sandy soil as backfill material after burying pipe, frost test was conducted to identify the effect of frost heaving when poor ground drainage was expected or groundwater level was high. The test material used was Jumunjin sand which was non frost susceptible and as indicated in Figure 1, particle distribution was concentrated on 0.3~0.8mm. Material properties of the specimen is as Table 2 and was classified as SP according to unified soil classification system.

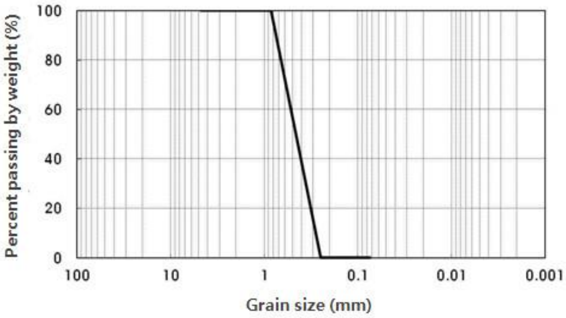


Figure 1. Grading Curve of Jumunjin Sand

Table 2. Material Properties of Jumunjin Sand

	Gs	emax	emin	D50	Cu	Cc	USPS
Jumunjin Sand	2.65	0.992	0.596	0.56	1.53	0.94	SP

2.2. Test Method and Result Analysis

Test method proposed by Shin *et. al*.(2010) was applied to frost test. Frost test device comprises specimen container and measurement part including instrument to measure swelling pressure and frost heaving pressure. Specimen container can accommodate total 4 specimens and measurement part that has the holder to accommodate load cell to measure frost heaving pressure and KVDT to measure dwelling pressure and the temperature was measured by depth using temperature sensor. All data was measured at an hour interval.

The specimen used for frost heaving test was 100mm diameter and 200mm thick, compacted to 70% relative density and saturated, and was frozen by one-side temperature drop method to the bottom while maintaining -15℃ on top. To prevent the moisture from being discharged during test, bottom and side of mould was treated for waterproof. Figure 2 & 3 show the frost heaving test result with Jumumjin sand, indicating swelling by 3.84mm and frost heaving pressure 839.1 kPa. Despite the fact that the specimen was considered non-frost susceptible, frost heaving was monitored when saturated under undrained condition.

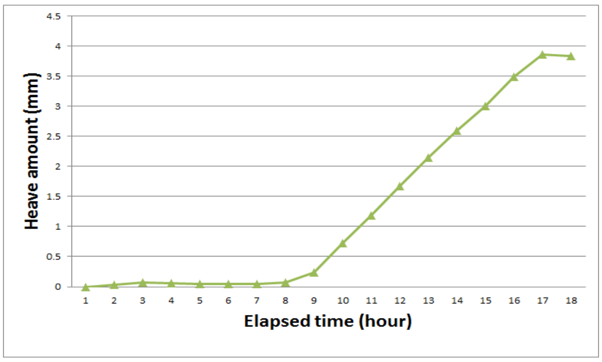


Figure 2. Frost Heave Amount Change Depending on Time

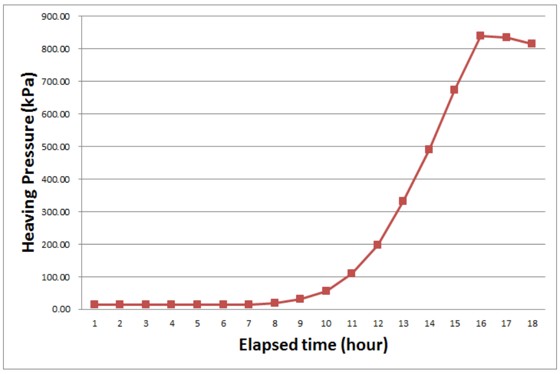


Figure 3. Frost Heave Pressure Change Depending on Time

The result demonstrated the possibility of frost heaving at freezing temperature depending on groundwater flow, saturation level, surrounding drainage condition, irrespective of the particle size of backfill material. Thus, when using the backfill material which has similar properties as Jumunjin sand, consideration of frost heaving shall be made, if surrounding ground is undrained state or less than frost penetration depth.

3. A Full-Scale Model Chamber Test

3.1. Test Method

A full-scale model test was conducted to identify the actual behavior of buried pipe in undrained and saturated non-frost susceptible ground.

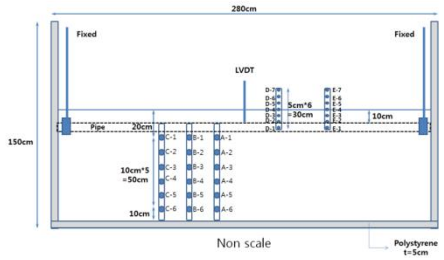
The chamber was 2 m × 2 m × 1.5 m and was designed to withstand maximum 10 ton at -40℃ or below. To simulate the freezing temperature, the chamber was placed in freezing chamber which could adjust the temperature. Freezing chamber was 5.1m high, 5m wide, temperature range ±30℃with tolerance ±0.5.℃.

Figure 4 shows the section & plan of chamber and diagram of internal temperature sensor. To simulate the unidimensional thermal conduction incorporating site condition, the bottom and the side of chamber was wrapped with 5cm-thick Styrofoam and then plastic vinyl was laid to prevent water leak before filling with sand up to 65cm high and spraying the water for saturation. After saturated, water contents was measured and after fixing corrosion-resistant stainless steel pipe (STKM500), 50mm diameter and 3mm thick, at both ends on sand, 15cm thick sand was laid again. Water content up to 15cm deep was 24.3%, void ratio 0.65 and relative humidity 80% while those less than 15cm deep were 24.7%, 0.66 and 77%, respectively (see Table 3) The specimen used for the test was same Jumunjin sand as frost heaving test.

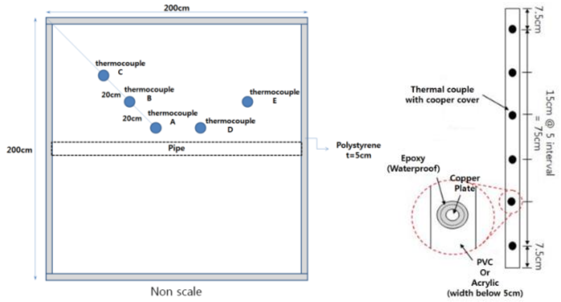
Table 3. Measured Initial Condition of the Specimen

Ground condition		Moisture content (%)	Void ratio	Unit weight (KN/m^3)	Relative density(%)
Upper layer (0-15cm)	Saturated sand	24.3	0.65	15.88	80
bottom Layer (15-80cm)	Saturated sand	24.7	0.66	15.78	77

Freezing chamber temperature was set at–15℃ and the sensor was placed to measure temperature variation inside the specimen and strain gauge to monitor the behavior of buried pipe. The center of buried pipe was connected to LVDT by connection rod so as to monitor the strain of buried pipe directly.



(a) Cross-Sectional Diagram of Test Chamber



(b) Plane diagram of test chamber (c) Thermocouple attached bar

Figure 4. Schematic Diagrams of Chamber Test

4. Analysis of the Result

4.1. Temperature Distribution around Buried Pipe

To monitor the ground temperature variation around buried pipe depending on freezing chamber, temperature sensors were placed on column at 15cm interval as seen in Figure. 4(c) so as to check the temperature variation by depth and temperature distribution depending on distance from buried pipe with the layout in Figure. 4(a) and Figure. 4(b).
As a result of monitoring temperature variation around the chamber, no variation depending on distance was monitored but the depth. Temperature distribution by depth depending on freezing time at point A and D, the nearest arrays from the buried pipe (see Figure. 4(a)) is indicated in Figure 5.

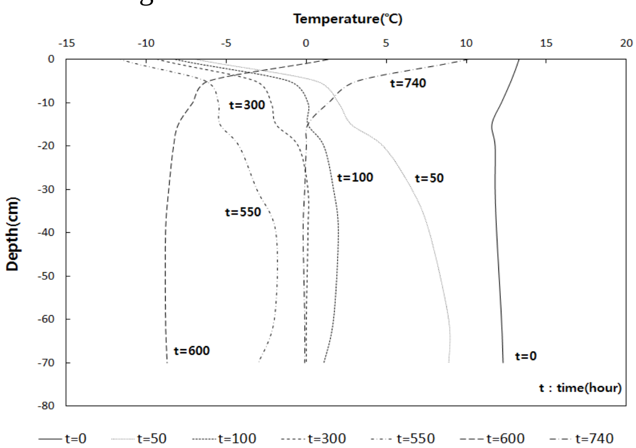


Figure 5. Temperature Distribution in the Specimen

The temperature fell gradually for initial 24 hours from 12℃ to –15℃ and temperature variation in chamber was monitored while maintaining the temperature at –15℃. After monitoring ground temperature maintained a certain level in 550 hours, temperature was gradually raised to allow the ground starts thawing and the behavior of buried pipe was

monitored for 1,000 hrs.
Frost penetration depth is dependent on temperature below 0 and duration time and freezing index obtained by quantifying it is used as design constant. Freezing index here refers to intensity of atmospheric temperature (below zero) and duration and cumulative effect which freeze the ground which is indicated in difference between maximum and minimum value on time curve for cumulative ℃.day (see Figure 6) When converting temperature condition realized in test into freezing index, 300 ℃·day is obtained. As such freezing index is similar with a 10-year intensity freezing index in Seoul and Gyeonggi area (KICT, 2013), it appears to be appropriate temperature in predicting the behavior of buried pipe depending on temperature in winter.

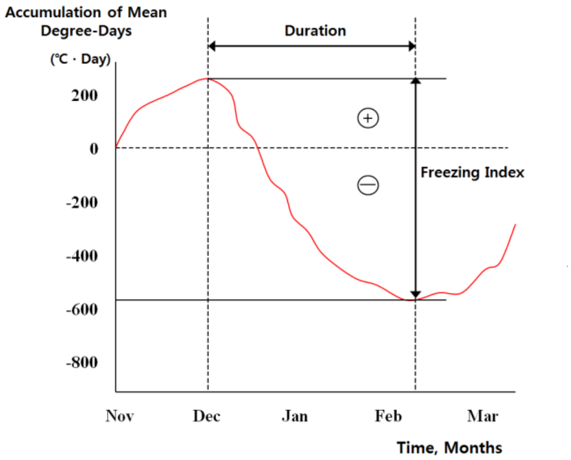


Figure 6. Freezing Index and Freezing Duration

Figure. 7 shows the variation in temperature and displacement at the pipe center. Temperature variation was based on average value measured by temperature sensor(D-1, E-1) placed at similar depth as buried pipe (Figure 4) While surrounding temperature dropped rapidly and maintained at a certain level due to phase change in pore water, displacement (heaving measured at mid-span) of buried pipe was monitored insignificant. As specimen temperature falls below zero when pore water phase change was finished, swelling occurred at the bottom of buried pipe leading to frost heaving.

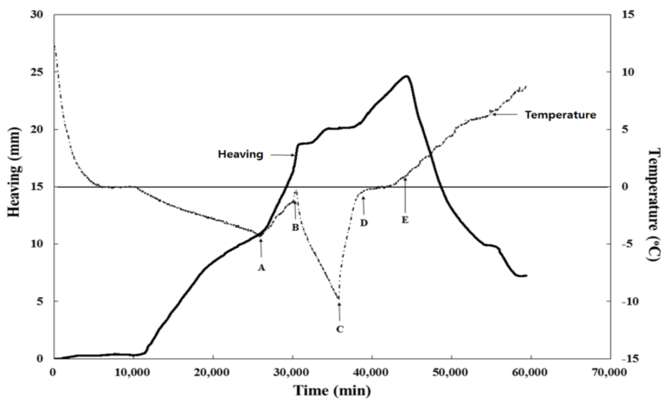


Figure 7. Temperature and Displacement at the Middle of the Buried Pipe

Initial thawing began at point A where heaving of buried pipe becomes weak. After setting freezing chamber temperature at 15℃, thawing began from the top of specimen and as surrounding temperature was getting higher, thawing began increasing (point B) and after setting freezing chamber temperature at –15℃, freezing began from the top of specimen and heaving was constrained (point C)After the specimens inside the chamber were all frozen, irrespective of the depth, temperature at the location where heaving was insignificant (point C) was set at 15℃ to start the 2nd thawing. While surrounding temperature rose to 0℃, heaving was insignificant but when the temperature was at 0℃ when phase change of pore water started (point D) heaving began occurring significantly around buried pipe and heaving reached to the maximum when phase change of pore water around buried pipe finished (point E) which was attributable to movement of pore water. As specimen on top began thawing, pore water moved to frozen specimen at the bottom of buried pipe, causing continuous freezing and heaving.

In conclusion, strain of buried pipe occurred during freezing in winter but also in spring when air temperature begins rising because of movement of pore water while deep ground was still frozen. In general, rupture to buried pipe was considered to be caused by strain by settlement resulting from ground thawing. Given the rupture in spring is attributable to potential heaving force at the bottom of buried pipe, site investigation seems to be necessary to verify the reliability of the result.

4.2. Shape Estimation of Buried Pipe

To identify the frost heaving and stress behavior on buried pipe, LVDT was placed at the center of buried pipe to check the displacement and strain gauge was also placed on buried pipe to check if the pipe was displaced.

The equation was developed using the strain of pipe to estimate the upward displacement by heaving as temperature falls which was compared with measured LVDT and bending stress on buried pipe was calculated to identify the plastic strain so as to determine the stability against freezing & thawing cycle of the material.

Finally, frost heaving force on buried pipe due to freezing expansion was calculated by applying strain value which was compared with frost heaving force to verify the reliability of the value from a full scale model test.

4.3. Estimation Equation of Strain of Buried Pipe

Given the displacement of the girder on which non-uniform distribution load is imposed is occurred in the form of biquadratic function to the length (x), displacement (y) of buried pipe which was fixed at both ends can be assumed as biquadratic polynomial to the length (x) as Equation 1 below.

$$y = ax^4 + bx^3 + cx^2 + dx + e \qquad (1)$$

Given displacement (y) and deflection angle (y') at both ends of buried pipe are fixed, $d = e = 0$ and relationship between Equation 2 and 3 are obtained by substituting $y(0) = y(L) = y'(o) = y'(L) = 0$.

$$y(L) = aL^4 + bxL^3 + cL^2 = 0 \qquad (2)$$
$$y'(L) = 4aL^3 + 3bL^2 + 2cL = 0 \qquad (3)$$

To estimate the three coefficients (a, b, c) included in Equation 2 and 3, three or more equations are needed. In this study, two additional equations from the curvature at the span center, besides two equations from displacement deflection angle, were used to estimate the coefficient.

When disregarding the lengthwise variation of flexible beam, curvature of beam (k) can be approximately estimated as quadric derivative term of vertical displacement.

$$k' = \frac{y''}{(1 + y'^2)^{3/2}} \approx y'' \qquad (4)$$

Strain (ϵ_t) on top and at bottom (ϵ_b) by pure bending at the span center of flexible beam could be indicated as Equation 5 and 6.

$$\epsilon_t = -k(d/2) \quad (5)$$
$$\epsilon_b = -k(d/2) \quad (6)$$

Where, d refers to diameter of steel pipe and thus the following equation could be obtained by stain value on top and at bottom from quadric differential equation to Equation 1 and relationship between equation 4, 5 and 6.

$$y_t" = 12ax^2 + 6bx + 2c = -2\epsilon_t/d \quad (7)$$
$$y_b" = 12ax^2 + 6bx + 2c = -2\epsilon_t/d \quad (8)$$

Strain on top (ϵ_t) and at bottom (ϵ_b) of steel pipe were calculated by removing temperature effect on gauge and axial strain measured on neutral axis based on values measured op top and at bottom at span center as indicated in Equation 9.

$$\epsilon_{t,b} = \epsilon_r - \epsilon_g - \epsilon_l \quad (9)$$

Where, ϵ_t or ϵ_b are the strain on top and at bottom of steel pipe after removing temperature effect on gauge and axial strain and ϵ_r is strain measured by the gauge on top and bottom of the steel pipe and ϵ_g is correction value to correct the temperature effect on gauge and ϵ_l is axial strain.

ϵ_g indicates the gauge value which is getting less depending on temperature and thus correction value was calculated by following equation given on manual.

$$\epsilon_g = -2.68 \times 10 + 2.42 \times T - 6.16 \times 10^{-2} + 3.93 \times 10^{-4} \times T^3 - 8.68 \times 10^{-7} \times T^4 \ (\mu m/m) \quad (10)$$

Axial strain of the pipe (ϵ_l) is determined from the mean strain value measured by the gauge on neutral axis at span center of the pipe. Equation 11 to calculate the coefficient value could be obtained from 2, 3, 7 & 8 and coefficient a, b & c could be obtained from equation 12 using the least square technique. Table 4 summarizes the steel pipe data and corrected measured data used for displacement shape estimation in Table 4.

$$\begin{bmatrix} L^4 & L^3 & L^2 \\ 4L^3 & 3L^2 & 2L \\ 12(L/2)^2 & 6(L/2) & 2 \\ 12(L/2)^2 & 6(L/2) & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -\frac{2\epsilon_t}{d} \\ \frac{2\epsilon_b}{d} \end{bmatrix} \quad (11)$$

Table 4. Specification of Steel Pipe

External Diameter (mm)	Thickness (mm)	Elastic modulus (GPa)	Length (mm)	Temperature, (℃)	Central strain of pipe, (10^{-6})		
					Upper	bottom	neutral axis (mean)
50	3	200	1440	20 (initial), -15 (final)	4283	-3785	2183

Displaced shape as a result of applying calculated coefficient value is as Equation 12. Figure 8 shows the comparison between estimation equation of displacement (Equation 12) and displacement measured at both ends and center of the pipe. Displacement at the span center was 20.2mm and the displacement at the span center was 20.9mm indicating 3.3% of error which is considered relatively accurate estimate of displaced shape.

As a result of checking maximum displacement at the center, 20.2mm corresponds to 40.4% of pipe diameter 50mm which far exceeds allowable deflection 5% as defined in water pipe design or buried pipe design criteria and is interpreted as performance deterioration or problem with stability.

$$y = 7.77 \times 10^{-11}x^4 - 2.24 \times 10^{-7}x^3 + 1.61 \times 10^{-4}x^2 \qquad (12)$$

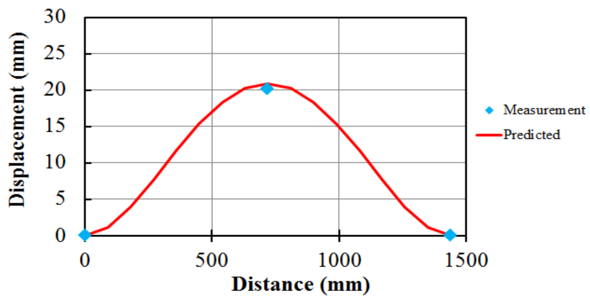


Figure 8. Measured and Predicted Displacement of the Buried Pipe

Bending tensile stress of the top of steel pipe calculated by estimation equation was 805.2 MPa, which was estimated on assumption of linear elastic behavior of steel pipe and indicated the plastic deformation exceeding yield tensile stress (380 MPa) Particularly bending stress of the top of steel pipe was 1242.4 MPa indicating plastic deformation at early stage when considering axial strain (2186μ).

Such result indicated the possibility of the rupture of buried pipe by frost heaving in surrounding ground under same freezing index in Seoul and Gyeonggi area, indicating the need of particular measure to secure the stability against frost heaving.

4.4. Estimate of Heaving Pressure to Buried Pipe

Estimate was made assuming that heaving pressure working on buried pipe is uniform over entire pipe. Maximum displacement at span center by uniformly distributed load on steel pipe, taking into account of point condition of fixing at both ends, is as Equation 13.

$$y\left(x = \frac{L}{2}\right) = \frac{\omega l^4}{384EI} \qquad (13)$$

Uniformly distributed load causing deflection measured at span center by frost heaving in Equation 13 was 44.3 N/mm and the heaving pressure calculated in a way of dividing uniformly distributed load by pipe width was 0.886 MPa(886 kPa) and heaving pressure calculated by frost heaving test was 839.1 kPa, which indicated heaving pressures from calculation and test were similar, demonstrating the reliability of the result from a full-scale model test.

5. Conclusion

This study is intended to identify the effect of the stress by frost heaving on rupture or deformation of buried pipe. Frost heaving test also indicated the occurrence of frost heaving in saturated sandy soil and a full-scale model test was conducted to monitor the effect on buried pipe and the result is as follows.

1. As a result of frost heaving test of sandy soil which is considered the non-frost susceptible, frost heaving was monitored under undrained saturated condition. In saturated sandy soil used for the test, swelling in volume was 1,92% and heaving pressure was 839.1 kPa.

2. In general, rupture to buried pipe was considered to be caused by strain by settlement

resulting from ground thawing. Given the pipe rupture occurred in spring was attributable to movement of melted pore water due to freezing at the bottom which causes potential heaving force, site investigation is necessary to verify the reliability of the result.

3. As a result of a full-scale model test, maximum displacement of buried pipe at freezing index 300 ℃·day was 20.2mm which corresponds to 40.4% of pipe diameter 50mm which far exceeds allowable deflection 5% as defined in water pipe design or buried pipe design criteria and is interpreted as performance deterioration or problem with stability.

4. Bending tensile stress on top of buried pipe on assumption of linear elastic behavior was 805.2 MPa which exceeds yield tensile stress of steel member (380 MPa) and may cause plastic deformation to buried pipe.

5. According to the test result, even in case of using sandy soil which is considered the non-frost susceptible, frost heaving may occur depending on water content and ground drainage condition and to secure the stability of buried pipe, it's necessary to verify the frost susceptibility of backfill material and drainage condition in surrounding ground.

Acknowledgments

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