AN EXPERIMENTAL STUDY TO EVALUATE FREEZING EARTH PRESSURE

MOTONORI ENOKIDO*

ABSTRACT

In recent years, LNG (Liquefied Natural Gas) has been used in Japan. Because LNG is stored at a very low temperature (-162°C), the use of LNG underground tanks presents new geotechnical problems, such as thermal analysis of the soil around the tank, the mechanical properties of frozen soils and an evaluation of freezing earth pressure.

This paper describes two kinds of tests undertaken to evaluate freezing earth pressure in stiff cohesive soil, for the purpose of checking an assumed design pressure adopted for the first LNG underground tank in Japan. This checking study comprises a preliminary laboratory test carried out to obtain an approximate value of freezing earth pressure and subsequently, a field test carried out on a model tank 2 m in diameter and 1 m high. An estimated value of maximum freezing earth pressure was obtained from the results of the field test, and it compared well with the result of analysis by the two-dimensional theory of elasticity. The relevance of the use of this experimentally obtained maximum value of freezing earth pressure seems to be proved, to some extent by the fact that the prototype LNG tank designed fortuitously on this value, has performed well for 10 years.

Key words : clay, earth pressure, field test, frost action, laboratory test, tank, underground structure (IGC : D 8/E 5)

INTRODUCTION

Underground tanks are used for storing large quantities of liquefied natural gas, LNG. Since LNG is kept at a very low temperature (-162°C), the use of LNG underground tanks presents geotechnical problems which have not been encountered before in civil engineering works, such as temperature distribution in the surrounding soil, mechanical properties of frozen soils and the change in earth pressure and expansion of soils by freezing. Of all these problems, an evaluation of the freezing earth pressure

may be the most important from a geotechnical point of view, however, few studies have been made so far on this particular problem (Enokido, 1978, 1979).

At the time of designing the first LNG tank in Japan, to be constructed within a stiff cohesive soil, locally named "dotan", it was not possible to measure the freezing earth pressure insitu on a full scale tank. Earlier studies of freezing earth pressure had been made by Kinoshita (1972) and Takashi (1972). It was judged however that the values of freezing earth pressure proposed by these previous studies could not be readily

* Professor, Department of Civil Engineering, Gunma University, 1-5-1, Tenjincho, Kiryu, Gunma.

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adopted for this design because of the differences in the test conditions and in the soil type. Design work for the prototype LNG tank was therefore based on a value of freezing earth pressure established using engineering judgement.

This paper describes the results of laboratory and field tests on the freezing earth pressure in the stiff cohesive soil, dotan. These tests were carried out after construction of the full scale LNG tank, in order to examine the relevance of the preliminary design value of freezing earth pressure previously adopted.

In recent years, a variety of sophisticated methods have been used for designing LNG underground tanks. The purpose of the present paper is to show the earlier state-of-the-art of measurement of freezing earth pressure at the time of construction of the first LNG underground tank in Japan.

LABORATORY TEST

Apparatus, specimens and test procedures

The test apparatus used in the laboratory test is shown in Fig. 1. A soil specimen was placed in the container and the void between the surface of the specimen and container wall filled with mortar. One end of the

Table 1. Index properties and strength

Specific gravity	G_s	2.70
Natural water content	w	29.0%
Liquid limit	w_l	46.2%
Plastic limit	w_p	27.0%
Plasticity index	I_p	19.2%
Unconfined compression strength		25 kgf/cm ² (2500 kPa)

specimen was in contact with a movable cooling tank comprising a rigid steel-plate box.

Undisturbed block samples of stiff cohesive soil were taken at the proposed construction site of the LNG underground tank. Representative values of index properties and unconfined compression strength of the soil are listed in Table 1. A block sample of the soil was trimmed to size of 40×20×20 cm, and placed in the container. Thermocouples were buried in the specimen for tracing the boundary plane between frozen and unfrozen zones of the soil. This boundary plane was called the freezing front in plan view. The distribution of water content in the specimen was measured before and after freezing.

In the freezing test, dry ice was put inside the cooling tank. At first, the soil in the vicinity of the cooling tank froze, then the size of the frozen zone increased with time, i.e., the distance between the cooling tank and the freezing front increased. As the soil froze, the soil tended to expand and the earth pressure acting on the cooling tank increased. Since the soil was very stiff, no appreciable earth pressure was considered to act before the test began. The earth pressure increase observed during freezing, therefore, was treated as the freezing earth pressure.

The freezing earth pressure was measured by the use of a load cell registering the total lateral thrust on the movable cooling tank. Vertical displacements of heave of the specimen were measured by dial gauges located along the center line of the top surface of the specimen. Horizontal expansions were obtained by measuring the distance between needles inserted through the top surface of the specimen at intervals of 2.5 cm. Horizontal displacement of the cooling tank was also

Fig. 1. Test apparatus

measured by dial gauges as shown in Fig. 1.

In all, the test was run on four specimens taken from the site.

Test results

Fig. 2 shows the progress of the freezing front at 0°C versus time for each of the test specimens Nos. 1 through 4. As can be seen in the figure, the four test results show a similar pattern of the progress of the freezing front. The relationship between the distance of the freezing front from the cooling tank (x , cms) and time (t , hours) may be approximated by the function $x = 4\sqrt{t}$.

As shown in Fig. 3, vertical displacements of the specimen increased with time, and the heave in the frozen part of the specimen was much larger than that in the unfrozen part. During freezing a remarkable horizontal expansion took place in the frozen zone, having maximum value of 0.8 mm for a length of 25 mm. In the unfrozen zone, in contrast, the horizontal expansion was very small. The results of water content measurements showed that the water content in the frozen

Fig. 2. Freezing distance and time

Fig. 3. Vertical displacements of the No. 3 specimen

Fig. 4. Displacement of cooling tank

Fig. 5. Freezing earth pressure and time

zone increased approximately 1.0 to 1.5 percent, whereas the water content in the unfrozen part decreased slightly.

As the soil specimen froze, the cooling tank moved horizontally as shown in Fig. 4. Since it is known that earth pressure largely depends on wall movement, the measured value of earth pressure in the present test,

Fig. 6. Freezing earth pressure and freezing distance

therefore, pertains only to the particular condition of wall movement shown in Fig. 4.

Fig. 5 shows the change in the freezing earth pressure with time in the four tests. The freezing earth pressure is seen to increase with time in the first eight hours, but no significant increase occurs thereafter. Fig. 6 shows the relationship between the freezing earth pressure and the freezing distance. Fig. 6 suggests the freezing earth pressure increases as the relative length of the unfrozen part of soil decreases which may infer an influence of a restraining nature. This means that the unfrozen zone of soil may absorb freezing earth pressure. So, the shorter is the unfrozen part, the more severe the restraining condition. Finally the maximum value of the freezing earth pressure in these particular tests was in the range from 4.6 to 8.5 kgf/cm² (460 to 850 kPa).

FIELD TEST WITH A MODEL TANK

The laboratory test described above was of a preliminary nature and with a special condition with regard to wall movement. In order to obtain the value of the freezing earth pressure under more realistic conditions, a field test was carried out at the site of the LNG tank. Stiff cohesive soil at the test site was overlain by a top silty layer,

7.5 m thick. The top silty soil was excavated and the surface of stiff cohesive soil layer levelled, a hole of 2.1 m diameter and 2 m depth was then excavated in the stiff cohesive soil, for installation of the model tank.

Model Tank

The model tank comprised a split concrete tube, as shown in Fig. 7. 2 m outer diameter, 1.4 m inner diameter and 1 m high. The tank was placed in the excavated hole, with its top surface about 1 m below the surface of the stiff cohesive soil. The void between the side wall of the tube and the excavation was filled with perlite mortar, strength $\sigma_7 = 60$ to 80 kgf/cm² (6 000 to 8 000 kPa) and thermal conductivity 0.45 kcal/m·h·°C. As shown in the figure, the tank was supported on a bearing to reduce friction on the base. An annular stainless steel cooling tank 10 cm wide, 80 cm high was inserted into the concrete tube, as shown in Fig. 7, to hold the liquefied nitrogen to be used as a coolant.

Four load cells were installed at the top and bottom of the split tube. In addition, two earth pressure cells were attached to the outer face of the tank, on section AC (see Fig. 7) at mid depth. Five other earth pres-

Fig. 7. Model tank (unit : m)

Fig. 8. Arrangement of earth pressure cells

Fig. 9. Multistage displacement gauges

sure cells were buried in the surrounding ground on section AC at mid depth as shown in Fig. 8.

A number of dial gauges were installed at ground surface in the vicinity of the tank for measuring vertical displacements of the ground surface. A multi-stage displacement gauge was installed for measuring radial displacement in the ground, as shown in Fig. 9. This gauge was a pipe consisting of separate segments and the change in length of each segment could be measured. As shown in Fig. 9, the gauge was installed in a horizontally bored radial hole at mid depth of the tank. Five different lengths of segments were installed, i.e. 30, 30, 40, 50 and 50 cm.

Eighty-three thermocouples were buried in

the surrounding ground for measuring the temperature distribution. They were located in two radial directions, OA and OB, (see Fig. 9), at three elevations, top, middle and bottom of the tank. In the test, liquid nitrogen was circulated through the cooling tank continuously for 21 days, then terminated.

Results of Measurements

Fig. 10 shows the distribution of the 0°C temperature in the ground from the start of liquid nitrogen circulation. Judging from the temperature distribution in the two directions, OA and OB, the freezing front expanded approximately as concentric circles to a distance of 1.3 m in 20 days.

It was observed that the tank moved up immediately after the start of freezing, and movement increased to a maximum value of 4.5 cm at 25 days. At that time, the maximum frost heave of the ground surface was 10 cm as shown in Fig. 11. The ground surface also moved outward as freezing progressed. The maximum value of this outward movement was 2 cm at a distance of 2 m from the tank wall.

Loads acting on the split concrete tube, were measured by the four load cells shown in Fig. 12. As for the case of the laboratory test, only incremental loads after freezing are considered. As shown in the figure, each of the four load cells recorded a similar increase in load in the first 60 hours. There-

Fig. 10. Temperature in the ground (Section AC)

Fig. 11. Vertical displacement on the ground

Fig. 12. Forces measured by load cells

after the load vs time relationship separates into two groups comprising the upper cells, L-1 and L-2, and the lower cells, L-3 and L-4. At 60 hours approximately, cracks were observed to develop on the ground surface. The slight decrease in the load measured by the upper cells may be due to the stress release associated with the development of these cracks. The lower cells, on the other hand, measured continuously increasing loads up to 150 hours, then showed no appreciable change in the load. Fig. 13 shows the state of cracking at 8 days.

Fig. 14 shows the results of the freezing earth pressure measurements obtained by

Fig. 13. Development of cracks at 8 days

the buried earth pressure cells, where again the incremental pressure after freezing is considered as the freezing earth pressure. Cells Nos. 1 and 2 were those attached to the outer face of the tank. The freezing earth pressure seems to increase suddenly when the soil in the vicinity of the cell started freezing. After this freezing stage, the records are somewhat erratic, however, the earth pressure increased rapidly at 21 days then

Fig. 14. Freezing earth pressure measured by buried earth pressure cells

Fig. 15. Lateral strain Versus time

decreased when the liquid nitrogen circulation was stopped.

Fig. 15 shows the change in lateral strains in the ground measured by the multi-stage displacement gauge. As shown in the figure, the lateral strain decreased as the distance from the tank increased. Decrease in the strain during the period 40 to 80 hours might be due to the development of the cracks previously discussed. The change in the distribution of lateral strain with time and distance is illustrated in Fig. 16. Progress of the freezing front is also shown in the figure.

Fig. 16. Distribution of lateral strain

Evaluation of the Freezing Earth Pressure

(a) Freezing earth pressure p_x acting on the freezing front

If the soil is assumed to be elastic, the earth pressure p_x can be evaluated by two methods. One method is to multiply the measured strain in the ground by the modulus of deformation of the unfrozen soil. The other is to use the theory of two-dimensional elasticity for a thickwalled cylinder. The solid line in Fig. 17 shows the

Fig. 17. Freezing earth pressure and freezing distance

Fig. 18. Model 1

relationship between the pressure p_x and the freezing distance, obtained by multiplying the measured lateral strain at the freezing front with the modulus of deformation of the unfrozen soil. The latter was taken as $4\,000\text{ kgf/cm}^2$ ($4 \times 10^5\text{ kPa}$) obtained from unconfined compression test results.

As previously described, ground surface as cracks were initiated at about 60 hours, and cracking progressed so the lateral strain measured after 76 hours was considered to be not reliable. It is seen in the figure that the freezing earth pressure p_x on the freezing front increases with the freezing distance. However, the maximum reliable value was little more than 5 kgf/cm^2 (500 kPa) at a freezing distance of 55 cm.

See Fig. 18, which shows thick-walled cylinder of inner diameter of $2b$, equal to the outer diameter of the tank; The freezing

front is at radius $(b+x)$, where x corresponds to the freezing distance. The general relationship between radial displacement δ_r at radius r and the freezing earth pressure p_x acting on the freezing front is given by

$$\delta_r = -\frac{1+\nu}{E} p_x \frac{(b+x)^2}{r} \quad (1)$$

where E and ν are modulus of deformation and Poisson's ratio of unfrozen soil respectively. Displacement δ_x at the freezing front is obtained by substituting $r=b+x$ into Eq. (1), yielding

$$\delta_x = -\frac{1+\nu}{E} p_x (b+x) \quad (2)$$

It is assumed here that the freezing earth pressure changes from zero to p_x as the radius of the freezing front increases from b to $b+x$. If the average coefficient of expansion during this process is assumed to be ξ then we get

$$\pi \{(b+x)^2 - b^2\} (1+\xi) = \pi \{(b+x+\delta_x)^2 - b^2\}$$

By assuming $\delta_x^2 \div 0$ this reduces to

$$\xi = \frac{2(b+x)}{(b+x)^2 - b^2} \cdot \delta_x \quad (3)$$

and from Eq. (2) and (3) we get

$$p_x = \frac{E}{2(1+\nu)} \cdot \xi \left\{ 1 - \left(\frac{b}{b+x} \right)^2 \right\} \quad (4)$$

Further, substituting $\delta_x = \xi_r x$, where ξ_r is the modulus of radial expansion, into Eq. (3), we have

$$\xi = \left(1 + \frac{x}{x+2b} \right) \xi_r \quad (5)$$

By substituting Eq. (5) into Eq. (4), the freezing earth pressure at the freezing front is given

$$p_x = \frac{E}{1+\nu} \xi_r \frac{x}{b+x} \quad (6)$$

Eq. (6) indicates that p_x increases with x , however, it converges to the following value when x becomes infinite.

$$\lim_{x \rightarrow \infty} p_x = \frac{E}{1+\nu} \xi_r \quad (7)$$

Fig. 19 shows the change in the measured radial displacement δ_r with time. As shown in the figure, the modulus of radial expansion ξ_r is calculated at times 12, 40, and 76 hours

Fig. 19. Change in radial displacement with time

respectively, which gives an average value of the modulus of $\xi_r = 0.0045$. Substituting this average value of ξ_r and $E = 4000 \text{ kgf/cm}^2$ ($4 \times 10^5 \text{ kPa}$), together with assumed value of $\nu = 0.3$ into Eq. (6), we get an expression for p_x as a function of freezing distance $x(\text{cm})$, thus,

$$p_x = \frac{4000}{1+0.3} \times 0.0045 \times \frac{x}{100+x}$$

$$= 13.85 \times \frac{x}{100+x} \quad (8)$$

This earth pressure p_x relationship is shown by the broken line in Fig. 17.

(b) freezing earth pressure p_b acting on the model tank

The earth pressure p_b can be obtained by the following two methods. One method is to consider that the measured force acting on the side of the model tank is the resultant of a uniformly distributed lateral pressure p_b . The other is to use the theory of two-dimensional theory of elasticity for a thick-walled cylinder.

Referring to Fig. 20, if the two forces N_1 and N_2 are taken as equal to N , then from equilibrium along the direction of the resultant force p , we get

$$2b \cdot p_b \cdot h = 2N$$

$$p_b = N/bh \quad (9)$$

The value of N can be taken as an average value of four forces shown A, B, C and D

Fig. 20. Forces acting on split model tank

Fig. 21. Relation between freezing earth pressure acting on tank and freezing distance

Fig. 22. Model 2

in Fig. 12, giving the earth pressure p_b shown by the solid line in Fig. 21. As stated before, the extent of reliable force data was confined to the time up to 60 hours which corresponds to a freezing distance of 55 cm. Fig. 21 shows that the maximum value of p_b calculated by this method is 7 kgf/cm^2 (700 kPa).

The alternative method is to use the theory of two-dimensional elasticity for a

thick-walled cylinder. As shown in Fig. 22, a thickwalled cylinder of inner diameter of $2b$ and outer diameter of $2(b+x)$ is considered; $2b$ and $2a$ correspond to the outer and inner diameters of the tank respectively. The radial displacement u_f of frozen soil is given by.

$$u_f = \frac{b^2 p_b}{E_f \{(b+x)^2 - b^2\}} \left[(1-\nu_f) + (1+\nu_f) \frac{(b+x)^2}{b^2} \right] \times b - \frac{(b+x)^2 p_x}{E_f \{(b+x)^2 - b^2\}} \times \left[(1-\nu_f) + (1+\nu_f) \frac{b^2}{b^2} \right] b \quad (10)$$

In the above expression, E_f and ν_f are the modulus of deformation and Poisson's ratio of the frozen soil respectively. On the other hand, considering a cylinder of outer diameter $2b$ and inner diameter $2a$, the radial displacement u_c of the outer face of the concrete tube is obtained by letting the internal pressure equal zero in the general formula for a thick-walled cylinder, yielding,

$$u_c = -\frac{b^2 \cdot p_b}{E_c (b^2 - a^2)} \left[(1-\nu_c) + (1+\nu_c) \frac{a^2}{b^2} \right] b \quad (11)$$

where E_c and ν_c are modulus of deformation and Poisson's ratio of concrete, respectively.

The condition that $u_f = u_c$ leads to the expression

$$\frac{p_b}{2} \left[\frac{(1-\nu_f)b + (1+\nu_f)(b+x)^2}{(b+x)^2} + \frac{E_f}{E_c} \times \frac{(b+x)^2 - b^2}{(b+x)^2} \frac{(1-\nu_c)b^2 + (1+\nu_c)a^2}{b^2 - a^2} \right] = p_x \quad (12)$$

This expression gives the relationship between freezing earth pressures p_b and p_x . When x increases infinitely, Eq. (12) becomes

$$\frac{p_b}{2} \left[(1+f) + \frac{E_f}{E_c} \frac{(1-\nu_c)b^2 + (1+\nu_c)a^2}{b^2 - a^2} \right] = p_x \quad (13)$$

The values of E_f and E_c were obtained from laboratory unconfined compression tests. When the temperature decreases, E_f increases and E_c is almost constant as shown in Fig. 23 (Tokyo Gas, 1976). On the outer face of the concrete model tank the temperature was -120°C for 20 days as shown in Fig. 10. The temperature at freezing front is 0°C . Considering that the average temperature of the frozen soil was -60°C , it was assumed that $E_f = 2 \times 10^4 \text{ kgf/cm}^2$ ($2 \times 10^6 \text{ kPa}$) and $E_c = 4 \times 10^5 \text{ kgf/cm}^2$ ($4 \times 10^7 \text{ kPa}$). By substituting the values $a = 70 \text{ cm}$, $b = 100 \text{ cm}$, $\nu_c = 0.17$, $\nu_f = 0.33$, $E_f = 2 \times 10^4 \text{ kgf/cm}^2$ ($2 \times 10^6 \text{ kPa}$) and $E_c = 4 \times 10^5 \text{ kgf/cm}^2$ ($4 \times 10^7 \text{ kPa}$) into Eq. (13) the following expression is obtained.

$$p_b = 1.36 p_x \quad (14)$$

Fig. 23. Modulus of deformation of frozen stiff cohesive soil

By using the values of p_x based on the theory of two-dimensional elasticity shown in Fig. 17, the corresponding values of p_b from Eq. (14) produce the broken line shown in Fig. 21.

As seen in Fig. 21, the values of p_b obtained by the two different methods agree well up to a freezing distance of 70 cm, and this result indicates that the probable maximum value of p_b is approximately 7 kgf/cm² (700 kPa).

Summary of the Model Tank Test

As shown in Figs. 17 and 21, the calculated values of p_x and p_b values do not seem to increase beyond the freezing distance range $x=50$ to 70 cm. This may be partly explained by the development of cracks, which may have relieved the stresses in the ground. The values of the freezing earth pressure based on the field measurements agree well with those obtained by the theory of elasticity over a specific freezing distance. To a degree, this may relate to the fact that the value of the modulus of expansion ξ_r used to calculate p_x is 4.5×10^{-3} , which may be considered to be within the commonly accepted range of elasticity. It should also be noted that the result of the present analysis does not necessarily imply that the freezing earth pressure can be evaluated by the theory of elasticity. This is because the present test was carried out under limited conditions and the result is not considered to be readily applicable to all full-scale tanks. Other factors requiring examination are the restraining condition in the vertical direction, the fulfillment of similarity criterion and the migration of water in the ground.

CONCLUDING REMARKS

It is considered fortuitous to have obtained the same order of freezing earth pressure acting on a wall in the frozen soil by two kinds of tests. The laboratory test was a preliminary test for the model tank test. It is encouraging that the results from the model tank test gave the maximum value of

freezing earth pressure p_b previously adopted using judgement since no other information on the freezing earth pressure in stiff cohesive soils was available at that time for designing the first LNG tank in Japan. The use of this maximum p_b value does not seem too unrealistic, because the actual LNG tank designed, fortuitously based on this same p_b value has exhibited good performance for ten years since the completion of its construction. For further studies on freezing earth pressure, however, it is considered essential to develop a reliable method for measuring the freezing earth pressure acting on a full-scale tank.

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NOTATION

- a =inner radius of tank
- b =outer radius of tank
- E =modulus of deformation of unfrozen soil
- E_c =modulus of deformation of concrete
- E_f =modulus of deformation of frozen soil
- h =height of tank
- N =normal force acting on split tank
- p_b =freezing earth pressure acting on outer surface of tank
- p_x =freezing earth pressure at distance x
- r =distance from center of tank
- u_c =radial displacement of outer face of concrete tank

u_f =radial displacement of frozen soil

x =freezing distance

δ_r =radial displacement of the r direction at r

δ_x =radial displacement of the x direction at x

ξ =average coefficient of expansion

ξ_r =coefficient of expansion in r direction

ν =Poisson's ratio of unfrozen soil

ν_c =Poisson's ratio of concrete

ν_f =Poisson's ratio of frozen soil

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