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The Behavior of House on Seasonally Frozen Ground

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SYNOPSIS This paper presents a case history of instrumented house with shallow foundation on the seasonally frozen ground. Variations of the soil frost penetration, the soil temperature, the cracks of the house, the displacements and the contact pressure on the base were systematically observed during freezing and thawing periods. It has been confirmed that the main reason why the cracks of the houses with shallow foundations occurred is that the development of the frozen depth is not uniform and the frost heaving and the redistribution of the contact pressures are unequal. This paper puts forward the principle of the effective depth of frost heaving and a new concept of foundation design method, which is adopted in the Chinese Code TJ7-74.

INTRODUCTION

In Chinese vast seasonally frozen areas there are many examples of damaged buildings because of their improperly arranged foundations. The purpose of testing a house with shallow foundation is to understand the behavior of foundation in process of freezing and thawing, and to find out the reasons that cause the damage of the house. Thus the depth and structure of foundation can be reasonably determined according to the nature of frost heaving in soil.

BASIC CONDITON OF TESTED HOUSE

The tested house is located in the suburb of Daqing. Local freeze index is 1998 degree-day. Depth of frost is 2.0-2.2m. Engineering geological section is shown in Fig.1. The index properties of soil are given in Table 1. The frost heaving on ground surface is 4.1cm.

TABLE 1. Index Properties of Soil

Soil Stratum	Grain Composition (%) 0.25-0.05 (mm)	0.05-0.005 (mm)	0.005 (mm)	Water Content w (%)	Density of The Soil (g/cm^3)	Liquid Limit LL (%)	Plasticity Index I_p
1	18.2	50.2	31.6	23.1	1.94	38.0	18.5
2	33.5	38.7	27.8	21.2	2.02	29.0	13.2

The tested house is a single-story building with brick-timber construction. Its length is 28m, width is 7.8m. Depth of rubble strip foundation is 0.7m. The interior geating temperature is about 15°c. The observed items and point arrangement are shown in Fig.2.

Cells embedded directly beneath the foundation base were covered with a thin sand layer, 2cm thick. Thermopairs were fixed on a wooden strip driven in the ground to a depth of 2.5m.

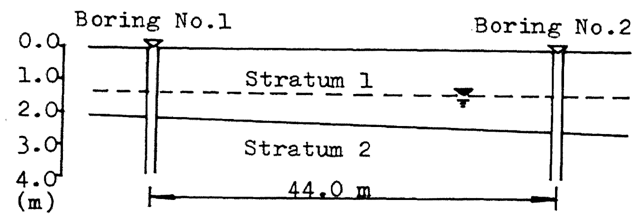

Fig.1 Engineering Geological Section

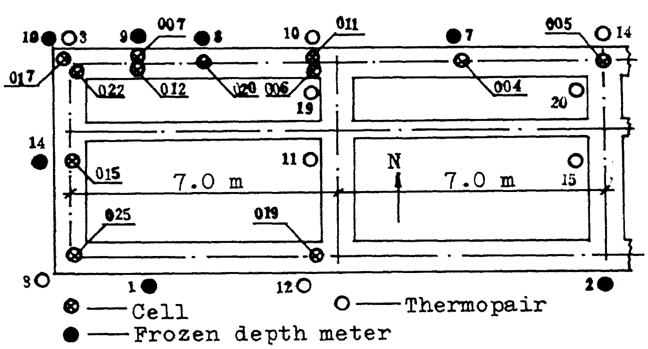

Fig.2 Observed Items and Point Arrangement

THE FREEZE-THAWING PROCESS AND TEMPERATURE FIELD OF SOIL UNDER BUILDING

Figure 3 shows the freeze-thawing process of soil under building at different points. From Fig.3 it may be seen that:

(1) The maxmium frost-depths of the different points did not arrive at the same time. The difference in frozen depth reached 49cm.

(2) The developement of soil freezing with time was not uniform. The freezing of soil under corners was earlier than under the middle part,

the freezing of soil under north wall was earlier than under south wall. Freezing date to get to the depth of the base of footing (eq.70cm) is shown in Table 2. The maximum difference of time was fifty days.

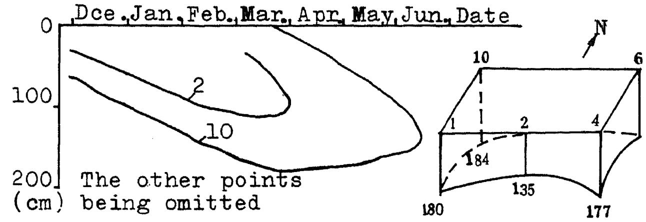

Fig.3 The Freeze-thawing process of Soil

TABLE 2. The Freezing Date to Get to The Depth of The Base

Place of Points	Middle Part of South Wall	Middle Part of West Wall	North-West Corner	Middle Part of North Wall
Date	24 Jan.	11 Dec.	3 Dec.	5 Dec.

TABLE 3. Thawing Process of Soil

Place of Points	Middle Part of South Wall	Middle Part of West Wall	North-West Corner	Middle Part of North Wall
Date to Get to The Base	18 Mar.	17 Apr.	28 Apr.	27 Apr.
Date Thawed Entirely	21 Mar.	6 May.	15 Jun.	20 May.
Average Thawing Speed (cm/day)	6.4	3.6	1.9	2.5

(3) The thawing process was also not uniform.The thawing date to get to the depth of the base and the date entirely thawed as well as average thawing speed for every point are given in Table 3.

It will be seen that the soil under middle part of wall thawed faster than under the corner; it thawed faster under south wall than under the north wall. When thawing began at northwest corner the soil under center of south wall had already thawed. At this moment the difference of thickness of freezing layer exceeded 1m. Thus the state of soil changed continuously throughuot the winter time.

2. The Temperature Field of Soil Around House

The temperature field around a heating house is unceasingly changed in winter. When the frozen depth reaches its maximum value, the temperature field of soil below the outside of the north wall is shown in Fig.4.

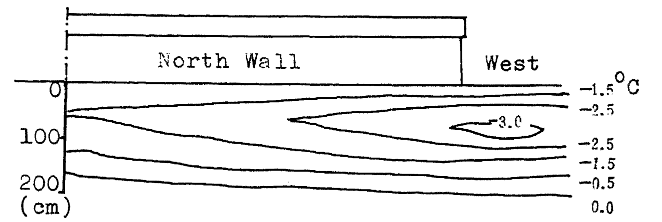

Fig.4 The Temperature Field During The Maximum Frozen Depth

In freezing stage the isotherm was basically parallel, and at a distance about one meter from the house it wound up. When the frozen depth reached its maximum value and the atmospheric temperature warmed up, the temperature of the frozen soil in the upper strata also went up. The temperature field in ground under the transversal section of the house is shown in Fig.5. The indoor positive isotherm protruded down, but the outdoor negative isotherm rapidly wound down from foundation, then became horizontal lines.

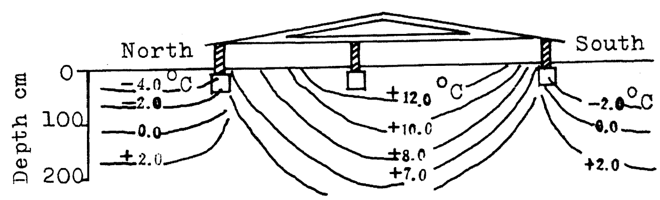

Fig.5 The Temperature Field Under The Heating House

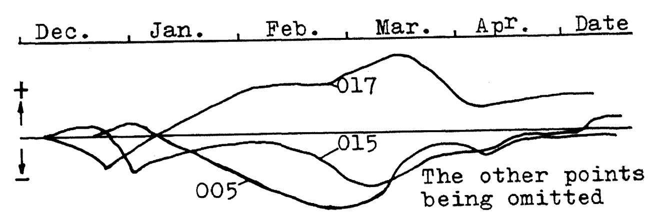

Fig.6 Variation of The Contact Pressures

THE CONTACT PRESSURE ON THE BASE

1. The Base Contact Pressure Along the Strip Foundation

Fig.6 shows the variation of contact Pressures with the time at the center and corner of north wall and west gable.

It will be seen that the contact pressures on the base changed severely as a result of unequal frost heaving resulting from disproportional frozen depth (for value and time) under foundation. Due to different thawing order of soil the contact pressure presented frequent change. After thawing, the value of contact pressure did not return to the one before freezing. The values of contact pressure along north wall and west gable are given in Table 4.

TABLE 4. The Value of Contact Pressure

Wall	North Wall				West gable	
Pressure Cell Number	004	006+ 011 avge.	012	022+ 017 avge.	015	025
Before Freezing (kg.f/cm^2)	0.37	0.26	0.28	0.37	0.65	0.44
When Frozen Depth is Maximum(kg.f/cm^2)	-0.34	0.49	0.18	0.69	0.20	0.48
After Thawing(kg.f/cm^2)	0.30	0.53	0.33	0.47	0.73	0.38

2. The Contact Pressure of Foundation Section

Fig.7 shows the curves of the contact pressure variation in the freezing-thawing process. Cell No.022 was under the inside of foundation and cell No.017 was under the outside. Before freezing to the base, the foundation was unloaded since it was affected by tangential frost-heaving forces. After freezing below the base, the outside contact pressure of foundation increased, and the inside one decreased. When the uplift of foundation reached maximum value, the outside contact pressure also reached maximum, and inside pressure reduced to nil. In stable stage of frozen depth, due to temperature rise in the frozen layer the outside pressure relaxed, and the inside pressure progressively increased.

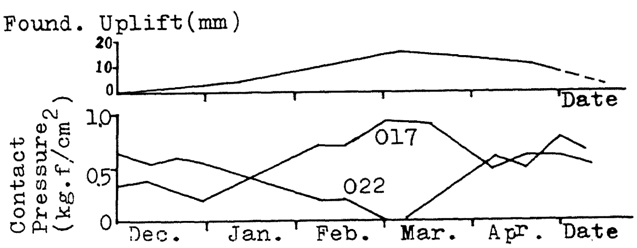

Fig.7 The Contact Pressure of Foundation Section

3. The Uplift of Foundation

The uplift of each measuring point in the freczing-thawing process is shown in Fig.8. It can be seen that the uplift of the foundation under the corner is bigger than under the middle part of the wall. The differential uplift reached 11mm. As a consequence the thawing settlement of corner often results in cracks on the corner.

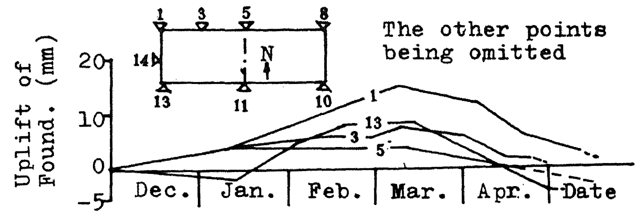

Fig.8. The Uplift of Foundation

Table 5 shows the relation between the uplift of foundation and contact pressure, which is obtained by field-test. It is obvious that the redistribution of contact pressure resulted from unequal frost heaving.

TABLE 5. The Relation Between Contact Pressure and Uplift of Foundation

Number of observed Point (see Fig.8)	1	3	5
Maximum Frozen Depth (cm)	184.2	162.0	152.0
Corresponding Contact Pressure (kg.f/cm^2)	0.69	0.49	0.35
Increment of Pressure, Relative to ones Before Freezing (kg.f/cm^2)	+0.32	+0.23	-0.17
Uplift of Foundation with respect to point No. 11(mm)	+13.5	+7.0	+2.5

Note: Positive sign shows rise.

ANALYSES OF HOUSE CRACKS

The types of cracks of a house with shallow foundation on seasonally frozen ground are usually vertical or inclined on the wall and horizontal at the window ledge. As to the tested house, the inclined cracks appearing in thawing period were at the northwest corner and the western end of south wall (Fig.9).

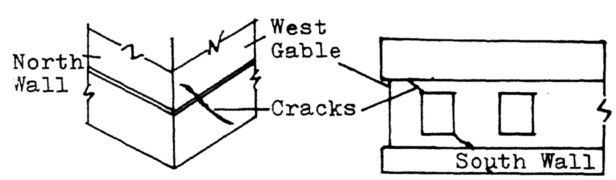

Fig.9. The Cracks of Tested House

The main reason of producing horional cracks is the difference of tangential frost-heaving forces which are produced in inside and outside of foundation and the redistribution of contact pressure on the base (Fig.10-a). For this reason, the foundation was turned and the horizontal cracks developed from inside to outside, and the stagger between upper and lower part of the wall was 1cm (Fig.10-b)

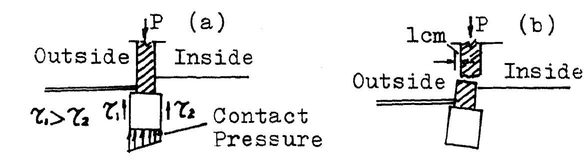

Fig.10 The Formation of Horizontal Cracks

DESIGN COUNTERMEASURES

1. The Nature of Frost Heaving in Soil

The field observation results show that:

(1) The frost heaving ratio K_d (the ratio between increment of frost heaving and increment of frozen depth) of clayey soil varies with the depth.

(2) The frost heaving does not proceed all the time during the freezing period, it ceases at a depth called effective depth of frost heaving which is less than the maximum frost penetration and the difference in depths is considerd to be allowable thickness of frozen layer beneath the foundation.

The frost heaving can be found in clayey soil only when its water content exceed some limiting value approaching to the plastic limit.

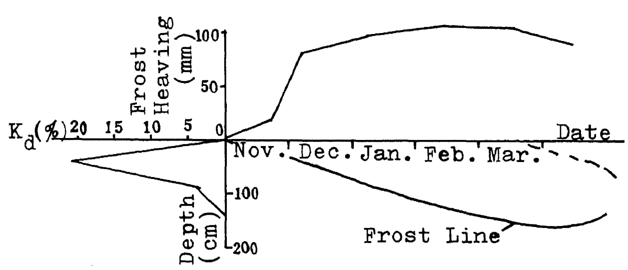

Fig.11 The Frost Heaving of Clayey Soil

If there is no supply from ground water (for closed system condition), the maximum average frost heaving ratio of saturated clayey soil can be determined by

$$K_d = \frac{1.09 r_d}{2 r_w} (W - W_p) \qquad (1)$$

where r_d is dry density of soil(g/cm^3), r_w is density of water(g/cm^3), W is water content(%) and W_p is the plastic limit of soil (%).

According to value of K_d, the frost heaving classification of clayey soil is shown in Table 6. The classification of frost heaving of fine sand or silt sand can be found in Chinese Code TJ 7-74 which is also base on the field observation.

TABLE 6. Classification of Frost Heaving of Clayey Soil

K_d (%)	1.0	1.0-3.5	3.5-6	6
Frost Heaving Classification	No	Light	Medium	Heavy
Water Content (%)	W_p+2	W_p+2—W_p+5	W_p+5—W_p+9	W_p+9

Note: When distance between ground water table and frost line is less than two meters the grade of frost heaving is raised by one grade.

2. Design Countermeasures

The minimum depth of foundation D_{min} can be determined by

$$D_{min} = ZM_t - d \qquad (2)$$

where Z is standard frozen depth, M_t is heating influence coefficient(M_t=0.85 for the corner, 0.75 for the middle part), d is the allowable thickness of frozen layer beneath the foundation in meters (d=0 for heavy heaving soil, d=0.15ZM_t for medium heaving soil, d=0.17ZM_t+0.26 for light theaving soil).

Some non-frost heaving materials are used for the backfill near the foundations of outside walls and or columns.

In conclusion, on the basis of analyzing the test results and field observations the measure produced here can prevent the house with shallow foundation from the frost heaving more economically.

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