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BY

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FROST-HEAVE UPLIFT FORCES ON FOUNDATIONS

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ABSTRACT

Foundations in frost-susceptible soils may be subjected to uplift forces and movements in two ways. When freezing occurs below the foundation footing ice lens growth results in the development of uplift forces which, in turn, cause structural displacements. Uplift forces may also develop when frost-susceptible soils are in contact with foundation walls or footing columns during freezing.

Les fondations situées dans un sol sensible au gel peuvent subir deux genres de forces de soulèvement. Lorsque la congélation se produit au-dessous de la rigole, la formation de lentilles de glace entraîne des forces de soulèvement. Il en résulte un déplacement de la construction. C'est ce qu'on appelle les "forces de soulèvement basales". Le gonflement dû au gel se produit également lorsqu'un sol sensible au gel se trouve en contact avec les murs de fondations ou les rigoles durant la congélation. Les forces engendrées par la formation de lentilles près de l'élément de fondation sont transmises à la construction par l'effet d'adhérence.

Introduction

In regions of seasonal frost, foundations of unheated structures may be subjected to forces and displacements resulting from ice lens formation. These problems occur only in frost-susceptible soils, i.e., in soils that support ice lens growth, which is the main cause of heaving. One solution is to prevent soil freezing in the vicinity of the foundation of the structure by using thermal insulation. This technique is not always suitable, however, for all types of unheated structures. If the designer appreciates the frost heaving problem as it relates to structures there are many ways he can assure that the stability of the structure is maintained despite the frost-susceptible nature of the foundation soils.

Frost heaving forces that cause damaging displacements to buildings are transmitted from the soil to the structure in two ways. If freezing occurs below the footings in frost-heaving soils, uplift or "basal heaving" forces invariably result. The problem is usually avoided by placing footings well below the maximum depth of seasonal frost penetration. Uplift forces that result when frost-heaving soils are in contact with foundation walls or footing columns are not so well understood. In this case the forces due to ice lens growth in the soil adjacent to the wall are transmitted by adfreeze bond or "frost grip." Such forces depend not only on the contact area between the soil and the structure but also on the size and geometry of the foundation (walls or columns) and the heaving characteristics of the soil.

A better understanding about the nature of the heaving problem and the forces involved has been obtained from recent field experiments. The objectives of the study were to determine the

a) basal heaving forces due to ice lens growth beneath a footing,

b) adfreeze uplift forces on foundation walls and steel piles of various diameters, and

c) the ground surface deformation associated with (b).

Site and Soil Conditions

The experimental site was located on the property of the National Research Council of Canada, near the eastern limits of the City of Ottawa. The soil, of post glacial marine origin (1), is reasonably uniform with depth and consists of about 70% clay-size particles and 30% silt-size particles. Its average moisture content in the autumn is about 44%. The soil is highly frost susceptible and characteristically heaves between 75 to 100 mm each winter in snow-cleared areas.

Experimental Methods

Reaction frames. - Suitably anchored reaction frames were used in measuring heaving forces of the experimental foundation units. The superstructure of the reaction frames consisted of six 12 1/2 steel I beams, 0.914 m long and anchored at the four corners in bedrock using 19-mm rock bolts with 32-mm expansion shells. Competent limestone bedrock is located at a depth from 3.5 to 6.0 m below ground surface. The expansion shells were installed 0.5 m below the bedrock surface. The reliability of each rock anchor assembly after installation was tested by applying a tension of about 110 kN for several hours.

Footing, foundation wall and steel piles. - A circular steel plate, 0.3 m in diameter and 25.4 mm in thickness, was placed at the ground surface to simulate a footing. The concrete block wall structure was 1.22 m long, 0.204 m wide and placed to a depth of 1.52 m with about 0.304 m protruding above the ground surface.

The 1.8-m-long steel piles were installed to a depth of 1.5 m below the ground surface. The diameters of the piles were 88.9, 168.4 and 323.9 mm. The results given are averages for two piles of each diameter.

Force measurements. - Calibrated Dillon mechanical compression gauges, with a capacity of 222 kN, were placed between the rock-anchored reaction frames and the footing, concrete wall, and the 323.9-mm-diameter piles. A 111 kN capacity gauge was used for the 168.4-mm piles, and 44.5 kN gauge for the 88.9-mm piles. Force gauges were read daily at about 0830 hr during the heaving period.

Deflection and deformation measurements. - Level surveys, referenced to an established stable benchmark, were carried out weekly on two sets of markers placed at 0.35-m intervals to a distance of 2.13 metres to determine the deformation of the ground surface around the structures. Level surveys were also used to confirm the stability of the reaction frames and to measure the vertical displacements of the experimental structures during the heaving period.

Results

Force measurements on the circular footing were made during the winter of 1968-69; the average frost heave for the site was 91.4 mm. The force measurements on the foundation wall were made during the winter of 1970-71; average heave on the site was 85.3 mm. Measurements on the steel piles were made during the winter of 1971-72; the average heave on the site was 79.2 mm. The site was always cleared of snow to obtain the maximum amount of frost penetration.

Figure 1 gives the daily force measurements, the calculated av-

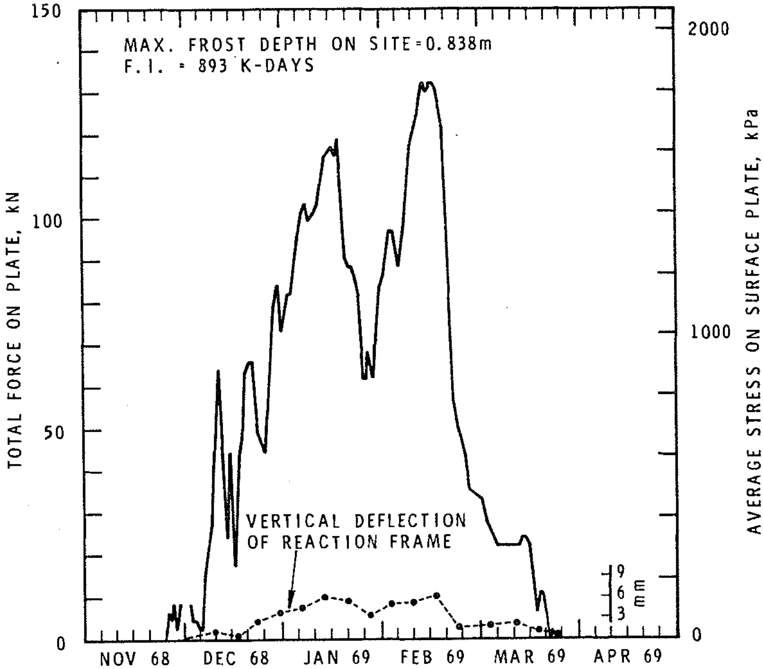

FIG. 1

Force measurements and pressures on 0.305-m diameter circular footing and vertical movement of footing, 1968-1969

erage stress directly beneath the 0.3-m diameter steel footing plate, and the deflection of the reaction frame. The magnitude of the forces developed due to ice lens growth clearly demonstrates that frost penetration cannot be permitted beneath footings in frost-susceptible soil if the stability of the structure is a functional requirement. Using the Boussinesq elastic theory of stress distribution (2) with values of 1 and 5 for the ratio E_f/E_u (E_f is the elastic modulus of the frozen layer and E_u the elastic modulus of the unfrozen soil) and 0.5 for Poisson's ratio, the maximum vertical stress was calculated to be between 62.0 and 82.7 kPa at the freezing plane when it was at a depth of 0.84 m. Stresses at the freezing plane associated with uplift of the footing were shown to decrease to zero at a radial distance of 1.83 m.

A maximum uplift force of about 75 kN on the 1.22-m-long concrete wall gave a calculated adfreeze value of about 25 kPa (Fig. 2). Average adfreeze values were obtained by dividing the total uplift force by the area of contact between the frozen soil and the surface of the wall. It may be noted, however, that the ground deformation pattern at right angles to the long dimension of the wall (Fig. 3a) was quite different than the pattern at the wall ends (Fig. 3b). The deformation of the frozen layer also extended to a greater distance from the wall than at the ends. In a recent paper (3) calculations based on the dependence of load on heave rate showed that about one-half of the uplift force was developed at the wall ends and the remaining half on the wall sides for this particular wall geometry and for this particular soil. Vertical stresses developed at the freezing plane due to ice lensing were calculated to range from about 20.7 to 34.5 kPa at a distance of 0.152 m from the foundation wall. These stresses along the freezing plane decreased to zero 1.83 m from the sides of the foundation and approached zero about 1.22 m from the wall ends. The pattern of deformation (Fig. 3) around the wall in a heaving soil is much the same as the behaviour of an ice cover in the vicinity of structures when subjected to a rapid change in water level (4, 5).

A viscoelastic theory relating adfreezing forces on structures of various geometries to heave and the rate of heave is still to be developed. Lack of progress with a theory applicable to field

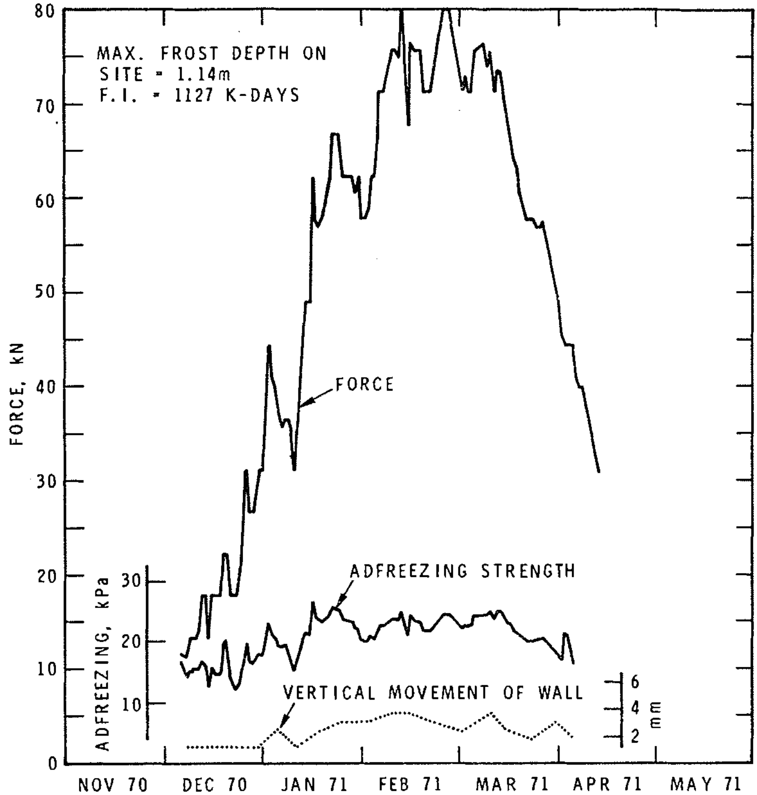

FIG. 2

Force measurements, calculated adfreeze strengths, and vertical movements of concrete block wall during heaving period, 1970-1971

conditions is understandable considering the continually changing temperature and the non homogeneous ice distribution in the frozen layer.

The development of force on the largest piles used in this investigation (323.9 mm diameter) and the adfreeze strength during

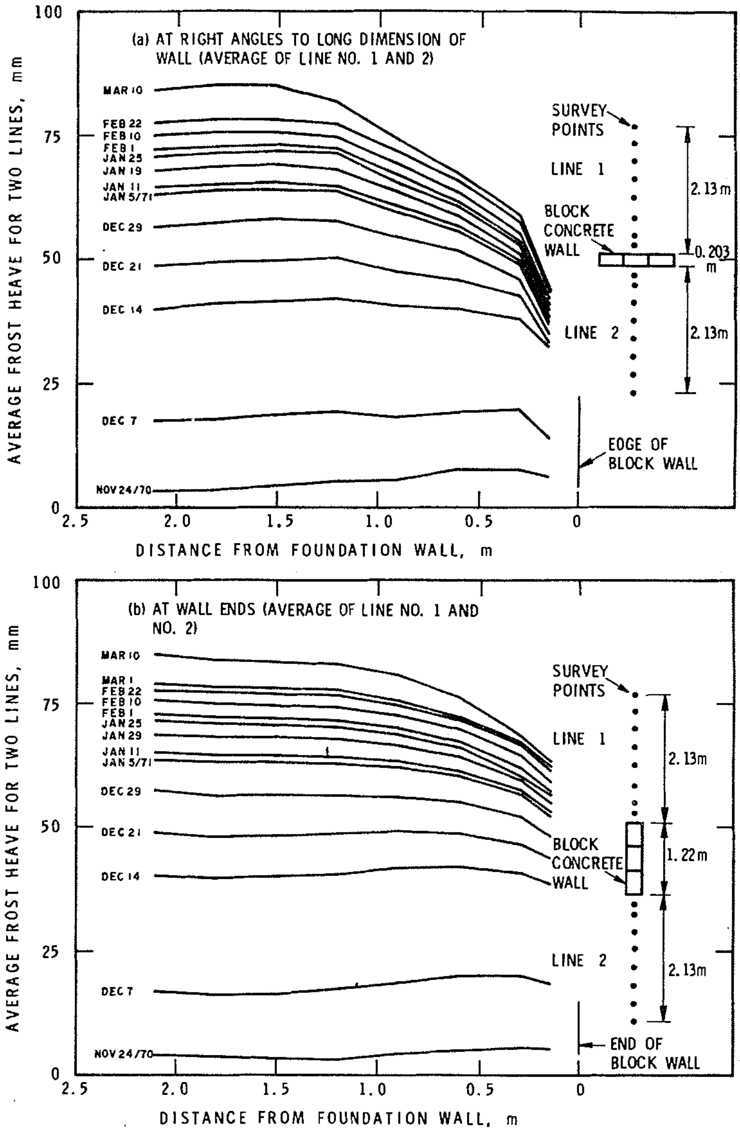

FIG. 3

Ground surface heave at ends of concrete block wall and at right angles to long dimension of wall, 1970-1971 one winter period is shown in Fig. 4. Soil deformation around

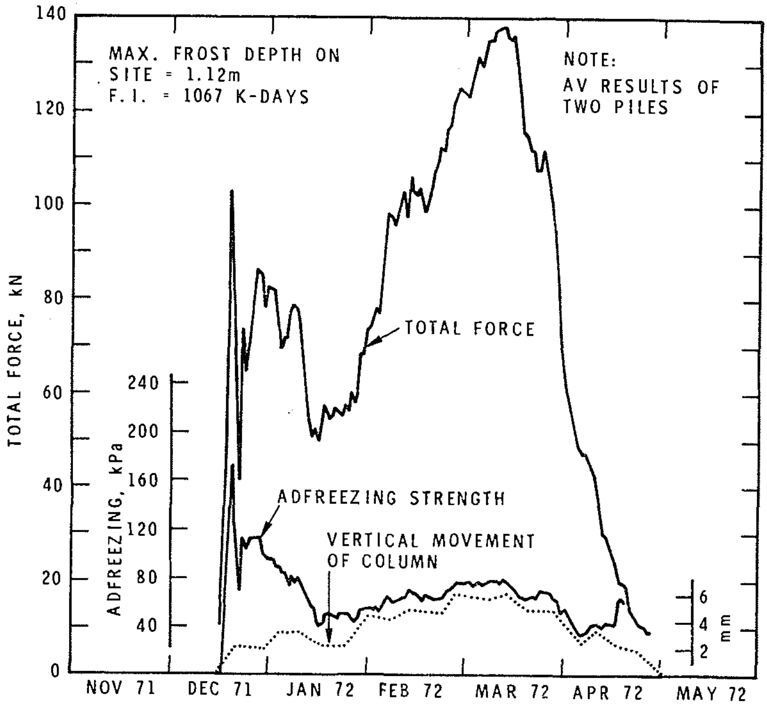

FIG. 4

Total force and adfreeze strength
for 323.9-mm diameter steel pile, 1971-1972

the piles was determined by precise level surveys on two sets of markers extending radially from the pile to a distance of 2.13 metres, i.e., to a distance where heaving was unimpeded by the structure. The general pattern was very similar to soil deformation around the concrete wall (Fig. 3). The 88.9 mm piles caused a decrease of 4.6 mm on the total heave; the 168.4 mm diameter piles reduced the heave by 24.4 mm; the 323.9-mm diameter piles reduced the heave by 30.5 mm. Unit adfreeze strengths based on the maximum measured force and contact area between frozen soil and pile were highest for the small piles and lowest for the largest piles. The maximum values were 255 kPa for the 88.9 mm piles, 200 kPa for the 168.4 mm piles and 173 kPa for the 323.9 mm diameter piles.

The pile material has also been shown to influence adfreeze values; highest values were recorded for steel, followed by concrete and then wood (4).

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