Frost Heaving of Soil and its Influence on Foundations and Railway Formations

Soulèvement du sol dû au gel et son influence sur les fondations des ouvrages et sur la superstructure de la voie ferrée

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Summary

Since the soil near a foundation will heave under the action of frost, the frozen bed will at first be distorted, but as soon as the depth exceeds about 0·3 m a continuous slide will develop.

The forces resulting from this action can be reproduced in tests carried out in a special press, using a sample of frozen soil moved continuously across a scale model foundation. The stability of a soil is a function of its temperature, and the authors found that their results agreed with loading tests which they carried out on full size foundations. They state that the upward force due to heaving can be calculated.

Determination of this upward force is based on the active zone which is much shallower than the overvall thickness of the frozen bed; it can be found analytically from an equation determining the conditions of moisture movement.

Uniform heaving does not present any particular problem in railway construction, unless it leads to dilution of the soil during thawing. Complications arise from uneven heaving. In planning methods of overcoming the problem, curves showing the variation of heaving with increased depth are very helpful. The authors consider a case of designing an anti-heave cushion.

Sommaire

Lors de la congélation et du soulèvement du sol près d'une fondation, la couche gelée subit d'abord un gauchissement ; ensuite, lorsque son épaisseur est supérieure à 0,3 m, on constate un glissement continu. Les forces qui se développent de ce fait peuvent être reproduites au cours d'essais effectués sur un échantillon du sol gelé qui se déplace d'une façon continue par rapport à un modèle de fondation placé sur une presse spéciale. Les valeurs de la résistance finale du sol gelé, obtenues expérimentalement, sont fonction de la température de celui-ci. Elles concordent bien avec les observations faites en place à l'aide de dynamomètres à corde vibrante et chargement de la fondation. On peut ainsi déterminer par le calcul la force de gonflement.

La détermination de l'importance du gonflement dans le cas d'une couche active dont une partie est comprise dans le niveau constamment gelé doit se baser sur l'épaisseur de zone à l'intérieur de laquelle le gonflement se produit, laquelle est sensiblement inférieure à l'épaisseur totale de la couche ; cette zone peut être déterminée analytiquement par la solution d'une équation donnant les conditions de la migration de l'eau par suite de l'aspiration des films ascendants.

Un soulèvement uniforme ne cause pas de grands dommages aux voies de chemins de fer, sauf du fait de l'augmentation de la teneur en eau lors du dégel. Les complications proviennent des irrégularités du soulèvement.

Pour établir les mesures à prendre contre les soulèvements, les graphiques d'intensité du soulèvement en fonction de la profondeur (6) ont une grande importance. Ces graphiques peuvent être présentés de façon différente.

Les auteurs de cette communication exposent un cas de dimensionnement des couches destinées à s'opposer au soulèvement par le gel.

1. The Effect of Heaving Upon Foundations

Damp soil congealed by frost will adhere to the lateral surfaces of a foundation. When frost heaving occurs, the forces developed in the frozen soil will tend to lift the foundation. Research carried out on the nature of soil surface movement, near the experimental foundations in Cherepovets and Igarka, revealed that the bed of frozen soil is warped initially when it is less than 0·3 m thick, and that this is followed by a continuous slide of frozen soil across the lateral surface of a foundation (Fig. 1) when maximum upheaval force will be developed.

Laboratory experiments have been conducted on a sample of frozen soil, continuously moved across a scale model foundation in a press designed by B. I. DALMATOV [1] (Fig. 2). The rate of movement was from 0·2 to 20 mm in 24 hours, equivalent to the rate at which frozen soil moves across a full scale foundation in practice.

During these experiments an increase in pressure was first noted without any substantial development in movement of the sample across the model foundation.

Thereafter the strains due to sliding rapidly accumulated until a maximum value was reached. This coincided with a drop of pressure in the press. Finally, with the sample continuing in motion across the model at a constant rate, gradual diminution of stress was observed as it tended towards a

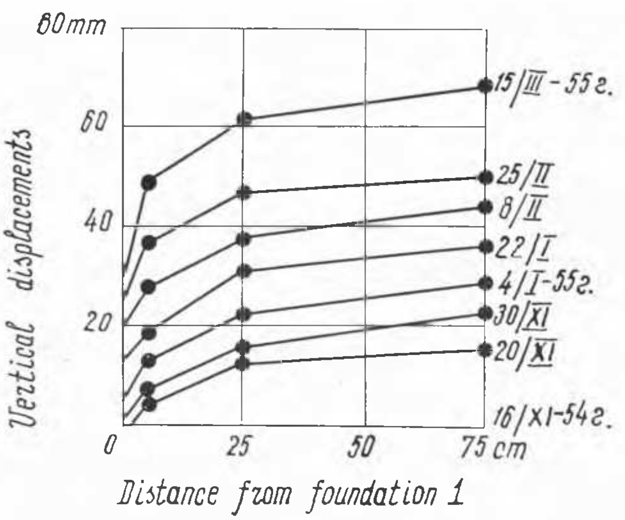

Fig. 1 Movement of soil surface near experimental foundation.
Déplacement de la surface du sol au voisinage d'une fondation expérimentale.

certain limit that represents the steady resistance of freezing of the soil to the material of the model foundation. A similar change in stress has been observed before [2].

The value of the stable resistance of freezing τ_s is found to be dependent on the temperature of the soil, and can be approximately determined from the parabola :

$$\tau_s = c + b\,|\theta|^m, \qquad \dots . \quad (1)$$

where $|\theta|$ is the absolute value of the soil temperature in degrees centigrade, and c, b, and m are parameters established experimentally.

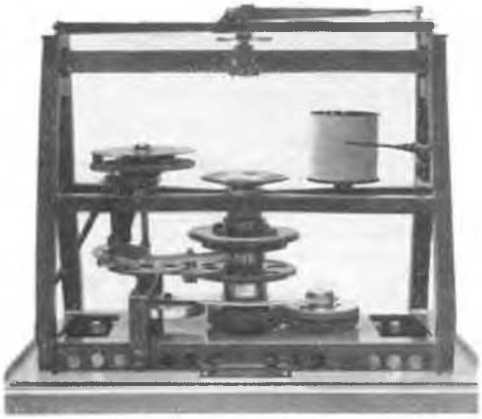

Fig. 2 Automatic beam press.
Presse à levier automatique.

Many experiments have proved that at temperatures up to —12° C, m can be assumed equal to 1. Then a linear relationship is obtained (Fig. 3) which is readily compatible with the values of tangential stresses measured by means of string dynamometers mounted in the experimental foundations [3]. The distribution of the heaving tangential forces, measured with the dynamometers, over the height of the foundation is shown in Fig. 4. It resembles the distribution of soil temperature over the depth of the frozen bed.

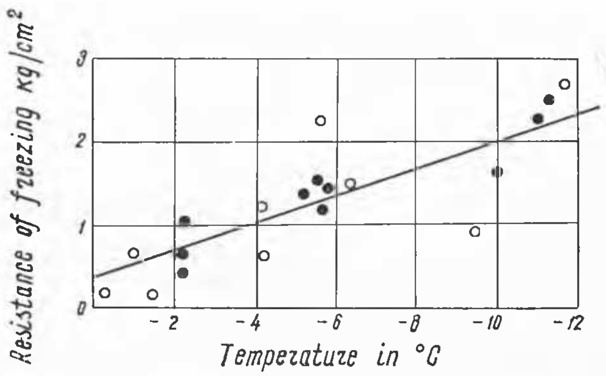

Fig. 3 Stable resistance of freezing of loose sandy soil : ● to concrete (as per laboratory trials) ; ○ to concrete foundation (as per string dynamometer readings), — in relation to temperature.
Résistance permanente à la congélation pour un sable pulvérulent; ● en présence de béton (d'après les essais de laboratoire) ; ○ en présence de fondations en béton (selon les données de dynamomètre), — en rapport avec la température.

The change of soil temperature with depth of the frozen bed is expressed as a linear relationship, the upheaval force T_{up} can be found by integrating τ_s over the area of freezing of the soil to the lateral surface of the foundation :

$$T_{up} = u \int_0^{H_a} \tau_{s,0}\, dH \approx u\, H_a (c + 0{\cdot}5 b |\theta_s|) \qquad \dots . \quad (2)$$

Here :

u = the perimeter of the foundation in the frost-affected zone ;
H_a = The active heaving zone ;
H = The depth of the frozen bed ;
$\tau_{s,\theta}$ = the stable resistance of freezing of the soil to the material of the foundation at a corresponding temperature and moisture content ;
θ_s = the absolute value of the temperature of the soil surface.

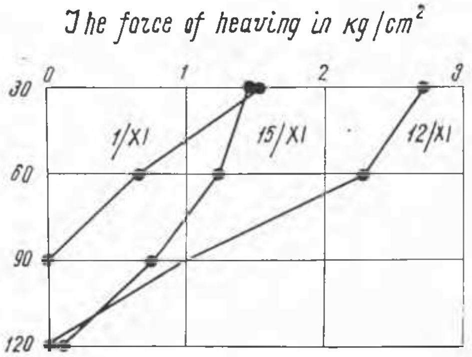

Fig. 4 Distribution of tangential heaving forces with depth of foundation.
Distribution des forces tangentielles de gonflement sur la profondeur de la fondation.

To verify the validity of expression (2) experiments were carried out on loams and sandy soils in Cherepovets and Igarka under conditions of natural freezing. The procedure adopted was to load the foundations as and when they manifested a tendancy to upward motion initiated by the upheaval forces.

A comparison of the calculated values with the actual load applied to an experimental foundation embedded in moraine loam is given in Fig. 5. When the load applied was less than the calculated force of heaving, the foundation was found to move upwards, and vice versa. This proves that heaving forces can be determined theoretically with sufficient accuracy.

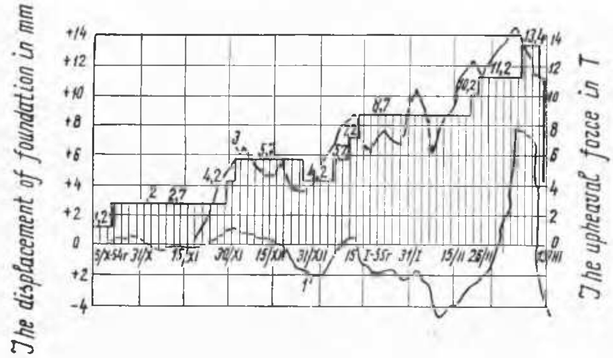

Fig. 5 Vertical shifting of foundation, and changing of upheaval force with time : 1) shifting of foundation ; 2) load applied, in tons ; 3) calculated upheaval force.

Déplacements verticaux de la fondation et modification du gonflement en fonction du temps : 1) déplacement de la fondation ; 2) charge appliquée en tonnes ; 3) force de gonflement calculée.

2. Determination of the Heaving Forces in the Case of a Merging Active Bed

To find T_{up} from expression (2), a knowledge of H_a is essential. Where seasonal freezing is concerned the latter value is generally equal to the maximum depth of freezing near the foundation. In the case of an active bed merging with the permanently frozen ground, H_a is substantially less than the depth of the active bed. It is well known that as damp loose or loamy soil is frozen, the water migrates from the bottom into the top layers of the active bed, which results in heaving of the top layers of the soil [4]. Inasmuch as the frozen ground debars water from penetrating into the active bed from below, and horizontal filtration in loams and sandy soils is normally insignificant, the moisture content of the soil in the bottom layers of the active bed falls substantially so that the soil will not heave as a result of freezing.

Observations of heaving at different levels have revealed that sandy soils and loams are subject to heaving down to 0·5 — 0·8 of the depth of the merging active bed. Hence, the value of H_a can be established through observation.

However, theoretical determination of H_a is also possible if it is assumed that migration of moisture mainly depends upon the wedging action of the forces developing in the water films (diffusing films), and the resistance to water filtration.

Using the tests of S. Mattson [5] as a basis, the wedging pressure of the diffusing layers p can be assumed to be equal to :

$$p = \frac{B}{W^n_d} - A \tag{3}$$

where W_d is the moisture content of the soil by weight, originating from the diffusing films, in parts,
and A, B, n are parameters established experimentally.

In the frozen zone, the moisture content in the liquid phase is given by the amount of unfrozen water W_u which is less than the water content W_d of the adjacent soil. This gives rise to a difference of wedging pressures in the diffusing film layers, resulting in a hydraulic gradient.

In order that a positive migration of moisture shall occur, the molecules of water penetrating the voids between the growing ice crystals and the soil particles, have to overcome the effective pressure which, in the absence of any load on the soil surface, is equal to the weight of the frozen bed γH. In coarse-grained soils, water molecules cannot penetrate rapidly into the gap. Therefore the weight of the frozen bed will be distributed over only a small proportion of the horizontal plan area of the freezing boundary surface. If the value of effective pressure within the potential limits of penetration of water molecules into the voids proves to be higher than the difference of wedging pressures, then no positive migration will occur. Hence, migration will develop under the conditions described by the following relationship :

$$\frac{B}{W^n_u} - \frac{\gamma H}{K_p} > \frac{B}{W^n_d} \tag{4}$$

Here K_p is the ratio of the plan of that part of the surface where water molecules can penetrate on to the horizontal plane through the gap between the ice crystals and the solid particles, to the plan of the freezing boundary surface on the same plane.

In the case of loose and loamy soils, K_p, is practically equal to unity, and the weight of the soil itself can thus be disregarded.

If it is then assumed that :

(1) moisture migrates owing to an hydraulic gradient brought about by the difference of wedging pressures with a corresponding difference in the moisture contents of the soil ;

(2) the coefficient of filtration of the soil is in linear relationship to the moisture content ;

(3) the depth of freezing increases, and the temperature of the soil surface decreases, with time, which roughly corresponds to the freezing conditions during the first half of winter in the North ; and

(4) the soil of the active bed is uniform before freezing, so that an equation can be written in the differential form :

$$\frac{\partial p}{\partial} = \frac{nK_0}{\gamma_w}\left(p + A + W_0\sqrt[n]{\frac{(p+A)^{n+1}}{B}}\right)\frac{\partial^2 p}{\partial z^2} \tag{5}$$

Here :

K_0 = the part of the coefficient of filtration that does not depend on the moisture content ;
γ_w = the specific gravity of water ;
W_0 = the maximum moisture content of the soil, at which practically no filtration in the soil is observed ;
z = the depth of the unfrozen layer.

An approximate solution of equation (5) makes it possible to calculate the depth of the heaving-active zone of a merging active bed. Calculations have shown [3] that the heaving-active zone decreases with the increasing water absorption of the soil. It increases with a higher rate of freezing, and depends on the depth of the active bed.

3. The Effect of Heaving on the Top Structure of Railway Formations

In regions affected by frost heaving, the Earth's surface frequently registers a rise of 30-40 mm, sometimes as much as 100 mm, during seasonal freezing of the soil.

Uniforms heaving on railways does not cause any operational difficulties, unless it leads to dilution of the soil when thawing occurs in the Spring.

In practice the term "heaves", is applied to *local* displacements of a railway track in space, caused by heaving.

Heaving irregularities on railways are differentiated as heave elevations, heave depressions and heave drops (Fig. 6). In deciding upon methods to be used to deal with heaves, in each particular case the heaves are of *purely local* origin.

The intensity of heave-forming processes varies with depth, and depends on several different factors, the influence of which can only be reckoned on an overall scale.

It therefore becomes necessary to determine the intensity of heave formation with depth for each particular section of line.

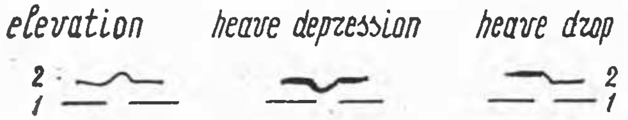

Fig. 6 Types of non-uniform heaving; 1) position of rails in summer time; 2) same in winter time.

Types de gonflement non-uniformes : 1) position des rails en été ; 2) position des rails en hiver.

Tests undertaken during the past decade by Russian research workers have helped [6, 7] towards defining the manner in which the intensity of heaving changes with depth.

In order to be able to estimate the intensity of heave formation with depth, G. M. Shakhunyants has prepared curves showing distribution of heaving intensity f in relation to depth (7), thus :

$$f = \frac{de}{dh} \tag{6}$$

Here $f = F(h)$ is the current value of heave formation intensity, being a function of distance h of an elementary heave-forming layer of thickness dh from the heaving boundary which lags behind the freezing boundary [8].

As the processing of numerous observation data indicates, heave formation curves may assume various shapes and they may even be discontinuous (Fig. 7). In a homogeneous soil these curves are often of triangular and rectangular shape.

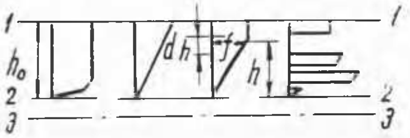

Fig. 7 Types of heave formation graphs : 1) soil surface; 2) heaving boundary; 3) freezing boundary.

Types de graphiques du gonflement, en profondeur : 1) à la surface du sol ; 2) à la limite inférieure du gonflement ; 3) à la limite inférieure de congélation.

The height of heaving of the soil surface e_0 is equal to the area of the heave formation graph :

$$e_0 = \int_0^{h_0} f\,dh \tag{7}$$

Heave formation curves enable several problems to be solved, which include the causes of heave formation as well as eliminating heaves in several ways, such as ballast evelation of the track [9], laying of heat insulating cushions, replacement of soil, levelling of the main area of the earth formation, and so forth.

As an example, let us consider a case where the heaves are eliminated by replacing heaving soil with non-heaving soil, the water being diverted from the spot where replacement takes place.

If the longitudinal conjugation of the non-heaving soil with the heaving soil be made in the form of vertical walls, then theoretically two vertical drops of height e_0 can be anticipated in place of one heave elevation with a height of $(e_1 - e_0)$, as shown in Fig. 8.

Obviously, the conjugation of the heaving soil with the nonheaving soil must be effected so that there would be a gradual transition between the sector where the rails rest on uniformly heaving soil and the sector where they rest on non-heaving substituted soil.

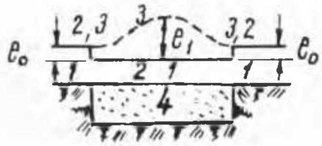

Fig. 8 Curves characterizing position of rails ; 1) position of rails prior to heaving ; 2) step-like position of rails after replacement of soil and heaving ; 3) same prior to replacement of soil ; 4) trench with non-heaving soil.

Courbes caractérisant la position des rails : 1) position des rails avant soulèvement ; 2) position en gradins des rails après remise en place du sol et soulèvement ; 3) le même avant remise en place du sol ; 4) fossé en sol non susceptible de gonfler.

It may be assumed, for instance, that this transition is required to follow some curve described by a differential equation :

$$\varphi = \frac{de}{dx} \tag{8}$$

Here $\varphi = F(x)$ is the current value of the variable slope of the given transition of the rails, and x is the horizontal distance from the starting point of conjugation of the anti-heave cushion to a given section of this conjugation.

Let us consider a case where replacement is extended up to the heaving boundary, and the non-heaving soil has the same thermal properties as the soil being replaced.

The problem here is to find the form of conjugation of the non-heaving soil with the heaving soil. The simplest solution is to use a combined graphical and analytical method (Fig. 9).

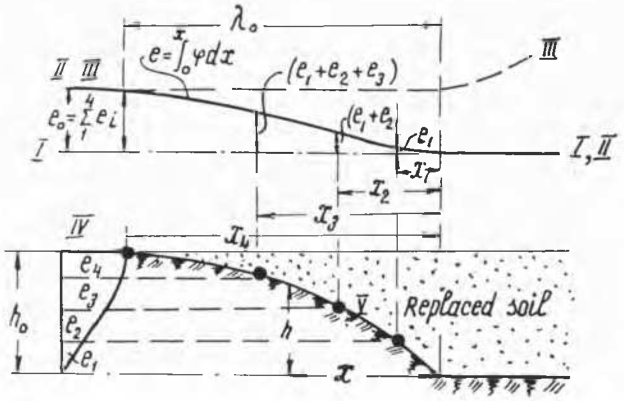

Fig. 9 The effect of combined graphical and analytical calculation of longitudinal conjugation of anti-heave cushion ; 1) position of rails prior to heaving ; 2) same after heaving and replacement of soil ; 3) same after heaving and prior to replacement of soil ; 4) heave formation graph of uniform heaving sector ; 5) conjugation curve being determined.

Graphique pour le calcul des couches contre le soulèvement : 1) position des rails avant soulèvement ; 2) position des rails après soulèvement et remise en place du sol ; 3) position des rails après gonflement et avant la remise en place du sol ; 4) intensité du soulèvement en profondeur dans un secteur de soulèvement régulier ; 5) courbe de corrélation cherchée.

The heave formation curve is divided into several sectors of which the boundaries are extended to the right by dotted lines. The area of each sector of the chart is calculated and designated as e_1, $e_2 ... e_i ...$

These areas represent the height of heaving resulting from the freezing of each respective layer.

The sections corresponding to the values e_1 $(e_1 + e_2)$, e_i, etc. are then found on curve $e = \int_0^x \varphi \, dx$. Vertical lines are drawn across these sections until they intersect with the corresponding horizontal lines. The points of intersection will naturally lie on the conjugation contour.

Analytically the equation of conjugation curve is obtained through a combined solution of equations (6) and (8) :

$$\int_0^h f \, dh = \int_0^x \varphi \, dx \tag{9}$$

The equation of conjugation curve will be :

(a) in the case of a rectangular heave formation curve :

$$h = \frac{h_0}{x_0} x, \text{ or}$$

(b) in the case of a triangular curve :

$$h = h_0 \sqrt{\frac{x}{\lambda_0}}$$

The most rational way to obtain a curve is by directly determining the average value of heaving of each layer into which the entire freezing zone is divided with a marginal allowance. Various system of differential heave gauges can be used for the purpose [6]. Another method consists in calculating the intensity of heave formation by the measurements of the moisture content of each one of the layers before the soil thaws [8].

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