doi: 10.18720/MCE.76.12

Normal stresses of frost heaving as function of excess moisture

Нормальные напряжения морозного пучения как функция избыточной влажности

O.V. Tretiakova,
Perm National Research Polytechnic University, Perm, Russia

Аспирант О.В. Третьякова,
Пермский национальный исследовательский политехнический университет, г. Пермь, Россия

Key words: frost heave; water sucking up; normal stress; soil interstices; soil interstitial volume; ice-cement; disjoining action of water films

Ключевые слова: морозное пучение; миграция воды из талой зоны; нормальное напряжение; поры грунта; свободное поровое пространство; замерзшая поровая вода; расклинивающее действие водных пленок

Abstract. Tangential and normal stresses are arises foundation area from the frost heave process. Currently known is the analysis of the tangential stresses based on adfreezing of the frozen soil to the lateral surface of foundation. However, the differences in values of normal stresses may be due to the fact that no single approach to normal stress evaluation has been developed yet. The purpose of our research is to work out the analysis method of the frost heave normal stresses. The stresses appear perpendicular to the surfaces of structures not allowing increase in the soil volume when cooled and frozen. Based on the author's research and other investigators' experience, analytical dependences for normal stresses of soil frost heaving were obtained. The stresses were calculated as a function of excess moisture, which volume exceeds the soil interstitial volume under freezing. The results obtained took into account such factors causing heaving process as ice formation during water freezing, accumulation of ice resulting from sucking up water and influence of unfrozen water. The proposed formulas allow for calculation of stresses in any kind soil.

Аннотация. При морозном пучении грунта, вблизи фундаментов развиваются касательные и нормальные напряжения. В настоящее время известен метод расчета касательных напряжений, основанный на определении сил смерзания грунта с боковыми поверхностями фундаментов. Однако значения нормальных напряжений морозного пучения в различных исследованиях имею большой разброс. Это говорит об отсутствии единого подхода к их расчету. Целью данной работы является разработка метода расчета нормальных напряжений морозного пучения. Последние возникают и действуют по нормали к поверхностям конструкций, которые ограничивают увеличение грунтов в объеме при охлаждении и промерзании. На основании исследований автора и опыта существующих работ получены аналитические зависимости для нормальных напряжений морозного пучения грунта в открытой системе. Значения напряжений вычислены как функция избыточной влажности, превышающей свободный объем пор грунта при промерзании. В полученных зависимостях учтены факторы, обуславливающие процесс пучения: льдовыделение при замерзании свободной поровой воды, влияние миграции влаги. Предложенные выражения позволяют выполнять расчет нормальных напряжений пучения для любого вида грунта.

Introduction

The seasonal decrease in temperature causes soil freezing leading to its volume increase. Uniform volume increase in a vast homogeneous bed does not usually result in occurrence of forces. However, any obstacle to volume increase can cause significant normal stress resulting in negative impact on embedded structures and foundations, which, in its turn, leads to heaving, deformation and cracks of structures. It has been studied by many authors [1–4]. Unbalanced loading of structures can cause horizontal shear and building tilt.

To prevent these negative effects, it is necessary to design structures capable of enduring the frost heaving stress based on the calculation [5–8] and modeling [9–12] or the frost heave stress must be partially or completely neutralized [13–15]. Proper evaluation of the frost heave stress can help solve the problem, which is possible after its detailed study. In Russia, N.A. Tsytovich gave basic theory of frost heave [16]. This research was carried out by many other authors. J.-M. Konrad [17, 18], R.L Harlan [19],

Третьякова О.В. Нормальные напряжения морозного пучения как функция избыточной влажности // Инженерно-строительный журнал. 2017. № 8(76). С. 130–139.

S.S.L. Peppin, R.W. Style [20] studied physics of frost heave. R.L. Michalowski [21] and Y. Zhang [22, 23] made some frost heave theoretical models.

The components of the frost heave process, being tangential and normal forces, are of different value and direction. V.S. Sazhin [24], V.I. Puskov [25], R.Sh. Abzhalimov [26] described mechanism of this process. This study is concerned with frost heave normal stresses.

The normal stresses of frost heaving are perpendicular to limiting surface, that is, lateral sides of foundations, which resist the increase in volume. Normal stresses acting on foundation bed occasion vertical uplift of foundation. Normal stresses acting on lateral surface causes the tangential forces.

Existing methods of studying the normal stresses of soil frost heaving comprise those used under laboratory conditions (in a closed and open system) [27–31] and under natural conditions (in open system) [32–36]. In a closed system normal stress values are determined by the pressure ice crystals under constrained water freezing and depend on the moisture properties of soil freezing. They may be significant and do not reflect the actual soil behaviour under natural freezing. When designing embedded structures, the stress-strain-state of the freezing soil in an open system is of great importance. The purpose of this study was to give a method of normal stresses under natural conditions in open system. The objectives were to study components of heaving stress in the open system, to determine mechanism the heaving normal stress and to develop a formula of the stress.

Methods

The open system is a soil body freezing under natural conditions. These conditions are formed on the experimental area, a construction site or in the soil body next to embedded structures built before. The open system is characterized by water sucking up from adjacent soil layers. In addition, this system is exposed to the influence of the stress-strain state of the adjacent layers subject to the shrinkage or increase in volume. In most cases, water sucking up in the unfrozen zone causes soil shrinkage in adjacent unfrozen layers.

Therefore, in the open system the normal heaving forces are caused by the pressure of ice-cement, influence of ice created by sucked up water, disjoining action of unfrozen water films and shrinkage of adjacent soil layers. In addition to soil properties, the values of normal heaving forces in the open system depend on the hydraulic conductivity of soil, compressibility of the underlying layers, structural rigidity and sensing forces of frost heaving.

Schematically heaving normal stress for the open system is shown in Figure 1. As can be seen in the figure, heaving stress in the open system consists of the following components,

- volumetric heaving stresses caused by accumulation of ice-cement resulting from crystallization of interstitial water;
- heaving stresses caused by influence of water sucking up due to
  a) crystallization of free capillary water,
  b) crystallization of bound water,
  c) disjoining action of unfrozen water films;
- shrinkage stress.

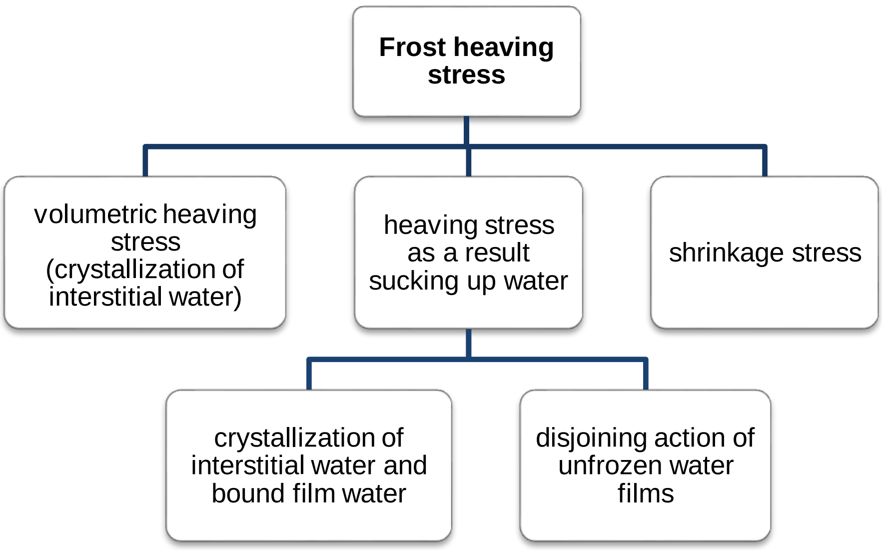

Figure 1. Components of heaving stress in the open system

The ice and unfrozen water whose overall amount is less than the soil interstices volume does not usually affect the walls of interstices and cause internal stresses in the soil. Accordingly there is no increase in the soil volume. Frost heave occurs if the amount of the frozen and unfrozen water exceeds the volume of the soil interstices. Unfrozen film water fed by sucking up, has a disjoining action on the freezing soil and is similar to swelling. In addition, “excess ice” acts as a “wedge” between the ice in the interstice volume and the walls of interstices. This results in stress in the soil causing displacement of the soil interstices, which in its turn, leads to increase in the soil volume. The normal stresses of frost heaving are developed due to foundations constraining action on the soil volume increase. Thus frost heaving stresses are, on one hand, the function of the soil porosity, on the other hand, the function of “excess moisture” resulting in the formation of “excess ice”, which the normal stresses reflect. “Excess ice” is the amount of ice exceeding the free interstice volume not filled by frozen and unfrozen film water. The normal stress value is also characterized by the rigidity of the foundation structure.

Condition under which soil heaving pressure occurs can be presented as follows

$$v_{ice} + v_{unfrouz.\,water} > v_{pore}\ , \tag{1}$$

where v_{ice}, $v_{\text{unfroz.water}}$ and v_{pore} are the ice-cement volume, volume of unfrozen film water and soil interstices, respectively.

Based on this, the expression for normal heaving stresses in the open system can be written as

$$\sigma_{heave} = \left(\sigma_{excess\ \ ice} + \sigma_{unfrouz.\,water} - \sigma_{shrincage.} \right) \cdot k_{an.}\,, \tag{2}$$

where “$\sigma_{excess\ \ ice},\ \sigma_{uvfroz.\ \ water}$” are the ice pressure and unfrozen water pressure due to water sucking up;

“$\sigma_{shrincage}$” is an unloading effect resulting from the soil shrinkage in the adjacent layers due to water sucking up;

“$k_{an.}$” is the anisotropy factor taking into account the direction of heaving forces.

To define the pressure of “excess ice”, we considered the distribution of water phase states in frozen soil (Figure 2). The total actual ice pressure results from two values, i.e.

a) ice-cement pressure together with 9 percent volumetric gain;

b) ice pressure caused by capillary and bound film water freezing due to water sucking up.

The (b) parameter (ice pressure) is a variable.

The $\sigma_{excess\ \ ice}$ (site 4b in Figure 2) reflects the difference between ice pressure due to total water sucked up (site 4a and 4b in Figure 2) and that of water sucked up in the interstitial volume (site 4a in Figure 2). The interstitial volume is the space free of ice-cement (site1 and 2 in Figure 2) and unfrozen film water (site 3 in Figure 2).

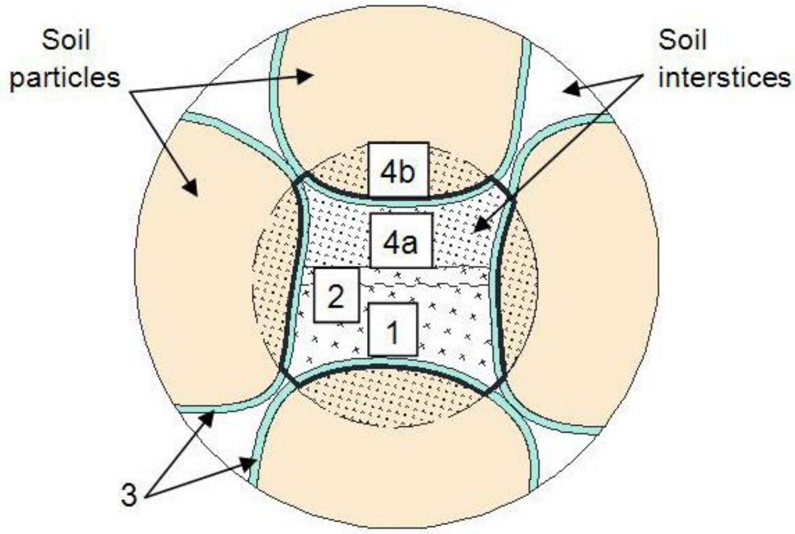

Figure 2. Water phase states in frozen soil
1 – ice-cement; 2 – 9 percent volumetric gain of interstitial water; 3 – unfrozen film water
4a and 4b – frozen sucked up water together with 9 percent volumetric gain (4a – in a soil interstices volume, 4b – in excess of soil interstices volume - "excess ice")

We deduced the expression of "excess ice pressure"

$$\sigma_{excess\ \ ice} = \sigma_{ice}^{migr.} - \sigma_{ice.}^{migr.} \cdot e \cdot (1 - w_w - 1.09 \cdot w), \tag{3}$$

where "*w*" is the natural moisture of soil and "w_w" is the water content due to unfrozen water, *e* – porosity ratio.

Upon rearrangement, expression (3) is as follows

$$\sigma_{excess\ \ ice} = \sigma_{ice}^{migr} \cdot [1 - e \cdot (1 - w_w - 1.09 \cdot w)], \tag{4}$$

Stresses due to the "excess ice pressure" in soil were expressed in terms of the Hook's law

$$\sigma_{ice}^{migr.} = h_{heave} \frac{E_M}{z}, \tag{5}$$

where "h_{heave}" is the displacement of soil under frost heave (cm), "E_M" is the deformation modulus of frozen soil (кN/cm^2) [37, 38], "*z*" is the depth of soil freezing vertically, soil thickness horizontally (cm).

Substituting the expression (5) in the expression (4), we obtained the formula for excess ice pressure

$$\sigma_{excess\ \ ice} = h_{heave} \cdot \frac{E_M}{z} \cdot [1 - e \cdot (1 - w_w - 1.09 \cdot w)], \tag{6}$$

Using the A.L. Nevzorov's formula [39], we expressed the displacement of soil under frost heave resulting from water sucking up as follows

$$h_{heave} = 1.09 \cdot SP \cdot \tau \cdot grad\ t, \tag{7}$$

where "*SP*" is the segregation soil potential (cm^2/hour· Celsius degree), "*t*" is the frost heaving time (hour) and "*grad t*" is the temperature gradient (Celsius degree/cm).

The expression (7) was substituted into the (6). By combining (6) and (7), we obtained the equation (8). The formula for excess ice pressure taking into account soil properties and frost soil thickness without regard to shrinkage and unfrozen water was transformed into

$$\sigma_{excess\ ice} = 1.09 \cdot SP \cdot \tau \cdot grad\ t \cdot \frac{E_M}{z} \cdot \left[1 - e \cdot \left(1 - w_w - 1.09 \cdot w\right)\right] \qquad (8)$$

The value of frost heave normal stresses equals the ‘excess ice’ pressure that results from «excess moisture» exceeding soil interstitial volume under freezing. We neglected the small pressure of unfrozen film water sucked up in frozen soil. The heave stress expression (2) was rewritten without regard to shrinkage and unfrozen film water as follows:

$$\sigma_{heave} = \sigma_{excess\ ice} \cdot k_{an.} \qquad (9)$$

Then, the expression (8) was substituted into the expression (9). Gravity water content was conversed to the volumetric water content. As a result the formula of normal stress as the function of moisture that resulted in formation of “excess ice” was obtained.

$$\sigma_{heave} = 1.09 \cdot SP \cdot \tau \cdot grad\ t \cdot \frac{E_M}{z} \cdot \left[1 - e \cdot \left(1 - w_w \cdot \frac{\rho_d}{\rho_w} - 1.09 \cdot w \cdot \frac{\rho_d}{\rho_w}\right)\right] \cdot k_{an}, \qquad (10)$$

where “ ρ_d / ρ_w” *is the* gravity water content to volumetric water content conversion factor.

The “excess ice” reflects the difference between ice pressure due to total water sucked up and that of water sucked up in the interstitial volume.

The formula of normal stress as the function of excess ice under total moisture capacity was written as

$$\sigma_{heave} = 1.09 \cdot SP \cdot \tau \cdot grad\ t \cdot \frac{E_M}{z} \cdot \frac{w_{sat} - w_w}{n \cdot (1 - w_w)} \cdot k_{an}, \qquad (11)$$

where “w_{sat}” – total moisture capacity, n – soil porosity.

Results

Table 1. The normal stresses calculated by formula

№ formula	Evaluation	σ_{heave} кN/m^2
10	$\sigma_{heave} = 1.09 \cdot SP \cdot \tau \cdot grad\ t \cdot \frac{E_M}{z} \cdot \left[1 - e \cdot \left(1 - w_w \cdot \frac{\rho_d}{\rho_w} - 1.09 \cdot w \cdot \frac{\rho_d}{\rho_w}\right)\right] \cdot k_{an}$	134
11	$\sigma_{heave} = 1.09 \cdot SP \cdot \tau \cdot grad\ t \cdot \frac{E_M}{z} \cdot \frac{w_{sat} - w_w}{n \cdot (1 - w_w)} \cdot k_{an}$	165

Table 1 displays calculation of frost heaving stress in clay by formula (10) and (11). The normal stresses of frost heaving in the open system were calculated as a function of “excess moisture” exceeding the free soil interstitial volume under freezing.

Table 2. The comparison of stresses calculated by formula to Guidance on design of substructures and foundations on heaving soil (1979)

	Methods	Thickness of frozen layer under the foundation base or on the lateral surface of foundation, *m*	Direction of frost heave normal stress	The frost heave normal stress, *kH/m^2*
The research	Formula evaluation	1.0	Horizontal lateral	134 – 165
Guidance on designing of substructures and foundations on heaving soil (1979)	Tabular date	1.0	Vertical	100 – 600

Table 3. The comparison of stresses calculated by formula to other authors' result

	Methods	Foundation depth, m	Thickness of frozen layer under the foundation base or on the lateral surface of foundation, m	Temperature of soil	Rate of heave mm/day	Direction of frost heave normal stress	The frost heave normal stress, kH/m^2
This research (2016)	Formula evaluation	1.0	1.0	-4.0	1.7	Horizontal	134-165
A.E. Fedosov (1935)	Laboratory test					Vertical and horizontal	150-180
N.N. Morareskul, N.A. Tsytovich (1950)	Laboratory test					Vertical and horizontal	500-800
B.I. Dalmatov (1954)	Field test	0.9 – 1				Horizontal	30 – 35
		1.45 – 1.72					64 – 66
V O. Orlov (1958) (frost zone out of contact with permafrost embedding on 4,5m)	Field test	1.09	0.18	–0.9	0.95	Vertical	160
			0.33	–1.4	1.36		510
			0.41	–2.4	1.35		950
			0.51	–4.4	1.22		3100
			0.6	–4.7	1.12		3800
			0.67	–4.9	0.96		4700
N.A. Tolkachev (1964)	Field test					Vertical	310-430
B.E. Slavin (1969)	Field test	1 – 6				Vertical and horizontal	182 – 322
E.A. Marov (1970-1971)	Field test	0.3	2.4			Vertical	760
V.S. Sazhin, V.Ia. Shishkin (1982)	Field test	1.2	0 – 1.2			Horizontal	1400 - 1600
E.D. Ershov (1985)	Laboratory test		0.5			Vertical and horizontal	220 - 620
Guidelines for accounting and preventing strains and forcers of frost heaving soils (Production and Research Institute for Survey and Construction) (1986)	Formula evaluation		0.9	–2		Vertical	63.9
				–4			183
A.G. Alekseev (2006)	Field test	2.0	1 - 2			Horizontal	20-190

Tretiakova O.V. Normal stresses of frost heaving as function of excess moisture. *Magazine of Civil Engineering*. 2017. No. 8. Pp. 130–139. doi: 10.18720/MCE.76.12.

The comparison of stresses calculated by formula with tabular data of RF Code is displayed in Table 2. As can be seen in Table 2, the normal stresses, calculated by formula (10, 11), agree with the tabular data of RF Code provided the anisotropy factor is taken into consideration.

The comparison of stresses calculated by formula with the results obtained by other researchers is displayed in Table 3.

So, the formula values of frost heave normal stress for layers of seasonal freezing proved true when compared with those, obtained by numerous researchers. The differences in values may be due to the fact that no single approach to normal stress evaluation has been developed yet.

Discussion

Division of frost heave stress into tangential and normal seems to be reasonable. Currently widely known is the analysis of the tangential stresses based on adfreezing of the frozen soil to the lateral surface of foundation. Research of academic specialists into frost heave direction led us to infer that it is possible to work out an analysis method of the heave normal stresses.

Research into frost heave normal stresses in open and closed systems seems to be representative. The normal stresses in the open system prove to be more reasonable as they take into account such factors causing heaving process as accumulation of ice due to sucking up water and influence of unfrozen water and stress-strain behaviour of soil below. Based on the research we can conclude that the normal stresses of frost heaving in the open system are a function of porosity and "excess moisture" whose volume exceeds the soil interstitial volume under freezing.

Soil and sucking up water that exceeds the soil interstitial volume after freezing causes increase in soil volume, which together with expansion constraint of foundations results in the heave normal stresses.

The comparison of stresses in Table 3 is worth mentioning that the normal stress values obtained in our research are comparable to those of other researchers. They correlate most with the results of B.I. Dalmatov (1954) [32] it taking into account the deformation modulus of the frozen soil. According to Table 3 our results can be associated with stress values obtained by A.E. Fedosov (1935) [40], B.E. Slavin (1969) [41], E.D. Ershov (1985) [28], A.G. Alekseev (2006) [35] and researchers from Production and Research Institute for Survey and Construction (1986). Our results agree with N.N. Morareskul' [27] and V.S. Sazhin' stresses [24] allowing for the anisotropy factor. Field tests carried out by E.A. Marov indicated significant increase of stresses depending on the thickness of the soil layer frozen [33]. Marov's results are comparable with our data under reduced layer soil thickness. Stress testing under the close system, i.e. in laboratory conditions, shows the high value stresses, which do not reflect the actual soil behaviour under natural freezing. In addition, research into the normal stresses in the permafrost region suggests these conditions be different from the seasonal freezing conditions (V.O. Orlov 1958) [42].

To make the analysis method work, several objectives need to be achieved:

- Statistical data on temperature and moisture of the soil at various depths within autumn-winter seasons should be provided, information on the freezing soil velocity is needed, which requires cartographic reference material.
- The method supposes revision of deformation modulus of frozen soil.
- To confirm the results obtained, a certain number of experiments should be carried out in different kinds of soil.
- The analysis method needs further interpretation in design programs.

Conclusion

As, a result of the research carried out it was found that

1. Frost heave occurs if the amount of the frozen and unfrozen water exceeds the volume of the soil interstices. Thus frost heaving normal stress is, on one hand, the function of the soil porosity on the other hand, it is the function of "excess moisture" resulting in the formation of "excess ice". "Excess ice" is the amount of ice exceeding the free interstice volume not filled with frozen and unfrozen film water after freezing.
2. The normal stresses in the open system prove to be more reasonable.
3. The formulas (10, 11) for the normal stresses of frost heaving in the open system as a function of excess moisture exceeding the free soil interstitial volume under freezing, and their results appear to

be relevant to the tabular data of RF Code available and other authors' results. The expression obtained make it possible to define normal stress in any hydrogeological and climatic conditions.

References

1. Modisette J.P., Modisette J.L. Pipe Line Frost Heave. *Pipeline Simulation Interest Group*. 2014. Vol. 1421. Pp. 1–8.
2. Kibriya T., Tahir L. Adfreeze forces on Lightly Loaded Pile foundations of Solar PV Farms in Gold Regions. *American journal of Civil Engineering and Architecture.* 2015. Vol. 3. No. 4. Pp. 109–117.
3. Babaei M., liu J., Staseff D. Numerical analysis of freezing and thawing influence on soil nail walls. *Conference: CGS GeoVancouver Conference.* Vancouver, October 2016.
4. Karlov V. D. *Sezonno promerzayushchie grunty kak osnovaniya sooruzheniy* [Seasonal freezing soils as a base of construction]: Doctorial Thesis: 05.23.02 Saint-Petersburg: SPbGASU, 1998. 349 p. (rus)
5. Golli O.R. *Integral'nye zakonomernosti moroznogo pucheniya gruntov i ikh ispol'zovanie pri reshenii inzhenernykh zadach v stroitel'stve* [Integral mechanism of frost heaving of soils and application of them in the performance of the engineering challenges in building]: Doctorial abstract: 05.23.02. Saint-Petersburg: VNIIG im. Vedeneeva B.E., 2000. 45 p. (rus)
6. Matveeva M.V. *Razrabotka algoritma chislennogo issledovaniya moroznogo pucheniya gruntov* [Logical design of frost heave numerical simulation]: Doctorial abstract: 05.13.18. Yakutsk. Yakutskiy gosudarstvennyy universitet im. M.K. Ammosova, 2009. 15 p. (rus)
7. Abzhalimov R.Sh. Printsipy rascheta maloetazhnykh zdaniy i podzemnykh sooruzheniy na puchinistykh gruntovykh osnovaniyakh [Calculation principles of low-storey buildings and underground structures on heaving foundation beds]. *Geotekhnika.* 2009. No.1. Pp. 25–33. (rus)
8. Zhou J. Z., Li D.Q. Numerical analysis of coupled water, heat and stress in saturated freezing soil. *Gold Regions Science and Technology.* 2012. Vol. 72. Pp. 43–49.
9. Cao H. Z., Liu S., Jiang F., Liu J. The theoretical study on frost heave for saturated granular soil-numerical simulation of 1-d ice segregating model based on equilibrium of force and phase. *Chinese Journal of Theoretical and Applied Mechanics.* 2007. Vol. 39. No. 6. Pp. 848–857.
10. Zhou G.-g., Hu K., Shang X.-y., Zhou J.-s. Test and numerical simulation on frost heave in frozen soils in intermittent freezing mode. *Procedia Earth and Planetary Science 1*. 2009. Pp. 512–518.
11. Michalowski R.L., Zhu M. Modeling of Freezing in Frost-Susceptible Soils. *Computer Assisted Mechanics and Engineering Sciences.* 2006. No. 13. Pp. 613–625.
12. Rotta Loria A.F., Frigo B., Chiaia B. A non – linear constitutive model for describing the mechanical behavior of frozen ground and permafrost. *Gold regions Science and technology.* 2016. Vol. 133. Pp. 63–69.
13. Kiselev M.F. *Meropriyatiya protiv deformatsiy zdaniy i sooruzheniy ot deystviya sil moroznogo vypuchivaniya fundamentov* [Protective measures against deformations building and construction due to frost uplift foundations]. Moscow: Stroyizdat, 1971. 104 p. (rus)
14. Babaei M., liu J. *Soil nailing for highway construction in Ontario – freezing and thawing effects on soil nail walls in Ontario.* Technical report. July 2016.
15. Guo R., Wang Z., Niu Y. Anti – frost heave of lining channel with concrete composite insulation based on TCR principle. *Chinese Society of Agricultural Engineering.* October 2015.
16. Tsytovich N. A. *Mekhanika merzlykh gruntov* [Mechanics of frozen soil]. Moscow: Vysshaya shkola, 1973. 636p. (rus)
17. Konrad J.- M. *Frost heave mechanics.* Ph. D. Thesis. Dept. of Givil. Eng. Univ. Edmonton Alberta, 1980. 472 p.
18. Konrad J.- M., Morgenstern N. R. A mechanistic theory of

Литература

1. Modisette J.P., Modisette J.L. Pipe Line Frost Heave // Pipeline Simulation Interest Group. 2014. Vol. 1421. Pp. 1–8.
2. Kibriya T., Tahir L. Adfreeze forces on Lightly Loaded Pile foundations of Solar PV Farms in Gold Regions // American journal of Civil Engineering and Architecture. 2015. Vol. 3. № 4. Pp. 109–117.
3. Babaei M., liu J, Staseff D. Numerical analysis of freezing and thawing influence on soil nail walls // Conference: CGS GeoVancouver Conference. Vancouver. 2016.
4. Карлов В.Д. Сезонно промерзающие грунты как основания сооружений: дис. д-ра тех. наук: 05.23.02 Санкт-Петербург: СПбГАСУ, 1998. 349 с.
5. Голли О.Р. Интегральные закономерности морозного пучения грунтов и их использование при решении инженерных задач в строительстве: автореф. д-ра техн. наук: 05.23.02 Санкт-Петербург: ВНИИГ им. Веденеева Б.Е., 2000. 45 с.
6. Матвеева М. В. Разработка алгоритма численного исследования морозного пучения грунтов: автореферат дис. канд. физ.-мат.наук: 05.13.18 Якутск: Якутский государственный университет им. М.К. Аммосова, 2009. 15 с.
7. Абжалимов Р. Ш. Принципы расчета малоэтажных зданий и подземных сооружений на пучинистых грунтовых основаниях // Геотехника. 2009. №1. С. 25–33.
8. Zhou J.Z, Li D.Q. Numerical analysis of coupled water, heat and stress in saturated freezing soil // Gold Regions Science and Technology. 2012. Vol. 72. Pp. 43–49.
9. Cao H. Z., Liu S., Jiang F., Liu J. The theoretical study on frost heave for saturated granular soil-numerical simulation of 1-d ice segregating model based on equilibrium of force and phase // Chinese Journal of Theoretical and Applied Mechanics. 2007. Vol. 39. № 6. Pp. 848–857.
10. Zhou G.-g., Hu K., Shang X.-y., Zhou J.-s. Test and numerical simulation on frost heave in frozen soils in intermittent freezing mode // Procedia Earth and Planetary Science 1. 2009. Pp. 512–518.
11. Michalowski R. L., Zhu M. Modeling of Freezing in Frost-Susceptible Soils // Computer Assisted Mechanics and Engineering Sciences. 2006. №13. Pp. 613–625.
12. Rotta Loria A.F, Frigo B., Chiaia B. A non – linear constitutive model for describing the mechanical behavior of frozen ground and permafrost // Gold regions Science and technology. October 2016.
13. Киселев М.Ф. Мероприятия против деформаций зданий и сооружений от действия сил морозного выпучивания фундаментов. М.: Стройиздат, 1971. 104 с.
14. Babaei M., liu J. Soil nailing for highway construction in Ontario – freezing and thawing effects on soil nail walls in Ontario // Technical report. July 2016.
15. Guo R., Wang Z., Niu Y. Anti – frost heave of lining channel with concrete composite insulation based on TCR principle // Chinese Society of Agricultural Engineering. October 2015.
16. Цытович Н. А. Механика мерзлых грунтов. М.: Высшая школа, 1973. 636 с.
17. Konrad J. - M. Frost heave mechanics. Ph. D. Thesis. Dept. of Givil. Eng. Univ. Edmonton Alberta, 1980. 472 p.
18. Konrad J.- M., Morgenstern N. R. A mechanistic theory of ice lens formation in fine-grained soils // Canadian Geotechnical Journal. 1980. Vol. 17. № 4. Pp. 473–486.
19. Harlan R.L. Analysis of coupled heat-fluid transport in frozen soil // Water Resources Research 9(5). 1973. № 5.

ice lens formation in fine-grained soils. *Canadian Geotechnical Journal.* 1980. Vol. 17. No. 4. Pp. 473–486.

19. Harlan R. L. Analysis of coupled heat-fluid transport in frozen soil. *Water Resources Research*. 1973. No. 5. Pp. 1314–1323.
20. Peppin S.S.L., Style R.W. *The physics of frost heave and ice-lens growth.* Oxford, 2012. 35 p.
21. Michalowski R.L, Zhu M. Frost heave modeling using porosity rate function. *International Journal for Numerical and Analytical Methods in Geomechanics.* 2006. No. 30(8). Pp. 703–722.
22. Zhang Y., Michalowski R. Thermal – Hydro – Mechanical Analysis of Frost Heave and Thaw Settlement. *Journal of Geotechnical and Geoenvironmental Engineering.* 2015. Vol. 141(7).
23. Zhang Y. *Thermal – Hydro – Mechanical Model for Freezing and Thawing of Soils.* Author's abstract of Civil Engineering doctoral thesis. University of Michigan, 2014. 201 p.
24. Sazhin V.S. *Vzaimodeystvie puchinistogo grunta s fundamentami, rabotayushchimi sovmestno s konstruktsiyami sooruzheniy* [Interaction of heaving soil with foundations that operates together with building]: Doctorial abstract: 05.23.02 Moscow: NIIOSP im. N.M. Gersevanova, 1989. 45 p. (rus)
25. Puskov V.I. *Silovye vozdeystviya moroznogo pucheniya gruntov na fundamenty sooruzheniy i metody ikh rascheta* [Force action of frost heave on building foundations and analysis methods]: Doctorial abstract: 05.23.02 Novosibirsk: Sibirskaya Gosudarstvennaya akademiya putey soobshcheniya, 1993. 37 p. (rus)
26. Abzhalimov R.Sh. *Zakonomernosti vzaimodeystviya puchinistogo gruntovogo osnovaniya s fundamentami maloetazhnykh zdaniy i podzemnymi sooruzheniyami i metody ikh rascheta* [Interaction mechanism of heaving ground bed with foundations of low-storey building and underground structures and its calculation principles]: Doctorial abstract: 05.23.02 Moscow: Mos. gos. un-t. putey soobshcheniya, 2011. 47 p. (rus)
27. Morareskul N.N. *Issledovanie normal'nykh sil pucheniya gruntov* [Investigation of frost heave normal forces]. Doctorial abstract. Leningrad: LISI, 1950. 26 p. (rus)
28. *Deformatsii i napryazheniya v promerzayushchikh i ottaivayushchikh porodakh* [Strains and stresses into freezing and thawing solid] ed. Ershova E. D. Moscow: Izd-vo Mosk. un-ta., 1985. 167 p. (rus)
29. Thomas H., Cleall P., Li Y.C., Harris C., Kern-Luetschg. Modelling of cryogenic processes in permafrost and seasonally frozen soils. *Geotechnique.* 2009. No. 59(3). Pp. 173–184.
30. Hyang Y.–H., Cai Z.–Y., Zhang C. Development of centrifugal model test facility for frost heave of channels. *Yantu Gongcheng Huebao / Chinese Journal of Geotechnica l Engineering*. 2015. No. 37(4). Pp. 615–621.
31. Ming F., Li D.-g. Experimental and theoretical investigations on frost heave in porous media. *Mathematical Problems in Engineering.* Vol. 2015. ID 198986. Pp. 1–9.
32. Dalmatov B.I. *Issledovaniya kasatel'nykh sil pucheniya i vliyaniya ikh na fundamenty sooruzheniy* [Investigation of frost heave tangential forces and their effect on foundations]. AN SSSR: Institut merzlotovedeniya, 1954. 60 p. (rus)
33. Marov E.A. Opredelenie normal'nykh i kasatel'nykh moroznogo pucheniya v polevykh usloviyakh [Definition of frost heave normal and tangential forces in the field]. *Sb. nauch. tr. Fundamentproekt vyp. 14: Materialy po proektirovaniyu slozhnykh fundamentov i osnovaniy i po proizvodstvu izyskaniy* [Design proceedings of elaborate foundations and survey]. Moscow: Fundamentproekt, 1974. Pp. 40-49. (rus)

Pp. 1314–1323.

20. Peppin S.S.L, Style R.W. The physics of frost heave and ice-lens growth. Oxford, 2012. 35 p.
21. Michalowski R.L, Zhu M. Frost heave modeling using porosity rate function // International journal for numerical and analytical methods in geomechanics. 2006. № 30(8). Pp. 703–722.
22. Zhang Y., Michalowski R. Thermal – Hydro – Mechanical Analysis of Frost Heave and Thaw Settlement // Journal of Geotechnical and Geoenvironmental Engineering. 2015. № 141(7).
23. Zhang Y. Thermal – Hydro – Mechanical Model for Freezing and Thawing of Soils. Author's abstract of Civil Engineering doctoral thesis. University of Michigan, 2014. 201 p.
24. Сажин В.С. Взаимодействие пучинистого грунта с фундаментами, работающими совместно с конструкциями сооружений: автореф. дис. д-ра тех. наук: 05.23.02 М.: НИИОСП им. Н.М. Герсеванова, 1989. 45 с.
25. Пусков В.И. Силовые воздействия морозного пучения грунтов на фундаменты сооружений и методы их расчета: автореф. дис. д-ра тех. наук: 05.23.02 Новосибирск: Сибирская Государственная академия путей сообщения, 1993. 37 с.
26. Абжалимов Р.Ш. Закономерности взаимодействия пучинистого грунтового основания с фундаментами малоэтажных зданий и подземными сооружениями и методы их расчета: автореф. дис. д-ра тех. наук: 05.23.02 М.: Мос. гос. ун-т. путей сообщения, 2011. 47 с.
27. Морарескул Н.Н. Исследование нормальных сил пучения грунтов. автореф. дис. к-та тех. наук. Ленинград: ЛИСИ, 1950. 26 с.
28. Деформации и напряжения в промерзающих и оттаивающих породах / под ред. Ершова Э. Д. М.: Изд-во Моск. ун-та. 1985.167 с.
29. Thomas H., Cleall P., Li Y.C., Harris C., Kern-Luetschg. Modelling of cryogenic processes in permafrost and seasonally frozen soils // Geotechnique. 2009. № 59(3). Pp. 173–184.
30. Hyang Y.–H., Cai Z.–Y., Zhang C. Development of centrifugal model test facility for frost heave of channels // Yantu Gongcheng Huebao / Chinese Journal of Geotechnical Engineering. 2015. № 37(4). Pp. 615–621.
31. Ming F., Li D-g. Experimental and theoretical investigations on frost heave in porous media // Mathematical Problems in Engineering. 2015. ID198986. Pp. 1–9.
32. Далматов Б.И. Исследования касательных сил пучения и влияния их на фундаменты сооружений. АН СССР: Институт мерзлотоведения, 1954. 29 с.
33. Маров Э.А. Определение нормальных и касательных сил морозного пучения в полевых условиях // Сб. науч. тр. Фундаментпроект вып. 14 Материалы по проектированию сложных фундаментов и оснований и по производству изысканий. М.: Фундаментпроект, 1974. С. 40–49.
34. Толкачев Н. А. Определение относительных нормальных сил морозного пучения грунтов // сб. науч. тр. НИИ оснований и подземных сооружений вып. 54 Основания и фундаменты. М.: Стройиздат, 1964. С. 165–170.
35. Алексеев А.Г. Определение горизонтального давления грунта на подпорные стены при сезонном промерзании-оттаивании: дис. к-та тех. наук: 05.23.02 М.: ОАО ПНИИИС, 2006. 190 с.
36. Jiang H., Tian Y. Test for frost heaving damage mechanism of rigid – soften composite trapezoidal canal in seasonally frozen ground region // Nongye Gongcheng Xyebao /Transactions of the Chinese Society of Agricultural Engineering. 2015. № 31(16). Pp. 145–151.

Третьякова О.В. Нормальные напряжения морозного пучения как функция избыточной влажности // Инженерно-строительный журнал. 2017. № 8(76). С. 130–139.

34. Tolkachev N.A. Opredelenie otnositel'nykh normal'nykh sil moroznogo pucheniya gruntov [Definition of frost heave relative normal forces]. *Sb. nauch. tr. NII osnovaniy i podzemnykh sooruzheniy vyp. 54: Osnovaniya i fundamenty* [Foundation engineering]. Moscow: Stroyizdat, 1964. Pp. 165–170 (rus)
35. Alekseev A.G. *Opredelenie gorizontal'nogo davleniya grunta na podpornye steny pri sezonnom promerzanii-ottaivanii* [Definition of frost heave horizontal pressure on retaining walls under seasonal freeze-thaw]: PhD Thesis: 05.23.02. Moscow: OAO PNIIIS, 2006. 190 p. (rus)
36. Jiang H., Tian Y. Test for frost heaving damage mechanism of rigid – soften composite trapezoidal canal in seasonally frozen ground region. *Nongye Gongcheng Xyebao/Transactions of the Chinese Society of Agricultural Engineering.* 2015. No. 31(16). Pp. 145–151.
37. Roman L.T., Kotov P.I. Modul' deformatsii merzlykh gruntov pri kompressionnykh ispytaniyakh [Deformation modulus of frozen soil under compression tests]. *Osnovaniya, fundamenty i mekhanika gruntov*. 2016. No. 5. Pp. 35–40. (rus)
38. Azmatch T.F, Sego D.C, Arenson L.U, Biggar K.W. Tensile strength and stress-strain 33ehaviour of Devon silt under frozen fringe conditions. *Gold Regions Science and Technology.* 2011. Vol. 68. No. 1–2. Pp. 85–90.
39. Nevzorov A.L. *Fundamenty na sezonnopromerzayushchikh gruntakh* [Foundations on seasonal freezing soil]. Moscow: Izd-vo ASV, 2000. 152 p. (rus)
40. Fedosov A.E. *Fiziko-mekhanicheskie protsessy v gruntakh pri ikh zamerzanii i ottaivani.* [Physico-mechanical process in soils under its freezing-thawing]. Moscow: Transzheldorizdat, 1935. 48 p. (rus)
41. *Tonneli* [Tunnels]: ed. D.I. Fedorova. Moscow: Transport, 1979. 176 p. (rus)
42. Orlov V.O. *Kriogennoe puchenie tonkodispersnykh gruntov* [Cryogenic heaving of finaly-dispersed soils]. Moscow: Izd-vo Akad. Nauk SSSR, 1962. 187p. (rus)

37. Роман Л.Т., Котов П.И. Модуль деформации мерзлых грунтов при компрессионных испытаниях // Основания, фундаменты и механика грунтов. 2016. № 5. С. 35–40.
38. Azmatch T.F., Sego D.C., Arenson L.U., Biggar K.W. Tensile strength and stress-strain 33ehaviour of Devon silt under frozen fringe conditions // Gold Regions Science and Technology. 2011. Vol. 68. № 1–2. Pp. 85–90.
39. Невзоров А.Л. Фундаменты на сезоннопромерзающих грунтах. М.: Изд.- во АСВ, 2000. 152 с.
40. Федосов А.Е. Физико-механические процессы в грунтах при их замерзании и оттаивании. М.: Трансжелдориздат, 1935. 48 с.
41. Тоннели: под ред. Д. И. Федорова. М.: Транспорт, 1979. 176с.
42. Орлов В.О. Криогенное пучение тонкодисперсных грунтов. М.: Изд-во Акад. Наук СССР, 1962. 187 с.

Olga Tretiakova,
+7(908)276-71-48; olga_wsw@mail.ru

Ольга Викторовна Третьякова,
+7(908)276-71-48; эл. почта: olga_wsw@mail.ru

Tretiakova O.V. Normal stresses of frost heaving as function of excess moisture. *Magazine of Civil Engineering.* 2017. No. 8. Pp. 130–139. doi: 10.18720/MCE.76.12.