International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 17 (2017) pp. 7007-7010

Reduction of Boundary Effects in Thermal Calculation of Tanks on Permafrost Soils

Evgeniy V. Markov[1], Sergey A. Pulnikov[2] and Yuri S. Sysoev[3]

[1,2,3] Industrial University of Tyumen, 38, Volodarskogo, Tyumen 625000, Russian Federation.

[1]Orcid ID: 0000-0003-0115-8734 & Scopus Author ID: 57194396650
[2]Orcid ID: 0000-0003-1592-0689 & Scopus Author ID: 57194389739
[3]Orcid ID: 0000-0002-5900-6322 & Scopus Author ID: 57194638286

Abstract.

The vertical steel tank is a shell structure that rests on the flexible or rigid foundations. Differential settlement is the most dangerous for any kind of foundation, because it leads to a change in the stress-strain state of the wall and roof or even to loss of structural stability. The appearance of differential settlement is most likely in the permafrost soils, which lose their bearing capacity during defrosting. Today, thermal calculations are usually performed on a computer with special software packages that are allow to solve all the complex problems associated with the conductive, convective and radiation heat transfer in the system: reservoir-ground-atmosphere. At the same time, using of complex empirical dependences of the heat exchange slows down the computing of problems. The problem of the speed of calculation is especially relevant in the technical and economic optimization problem. The increase of the calculation speed is possible in two ways: the increase of the size of the finite elements or reducing the size of the calculated area. In this paper, the second method of increasing of the calculation speed is considered. Since the reduction of the size of the calculated domain leads to increasing of the boundary effects, which distorts the real temperature distribution, the authors solved the problem of determining of the computational domain size, which has the smallest size and allow finding the solution with desired accuracy. The last allows reducing the number of finite elements and the computing time. Laplace equation, theory of Fourier-Bessel series and theory of the Green's function for a half-space was used to solve the problem for stationary thermal conductivity with cylindrical symmetry. The analytic expressions for an approximate computation of the absolute values of boundary effects were deduced. This expression was used to create the procedure for determining the optimum depth and radius of the computational domain.

Keywords: differential settlement of permafrost soils, vertical steel tank, boundary effect, optimal size of the computational domain

INTRODUCTION

The tank farm is one of the most important facilities in the oil industry. Sustainability and trouble-free operation in the conditions of permafrost soils (PS) is often complicated by the need for petrolium product storage at a positive temperature. Technogenic thermal action leads to thawing of PS at the base of tanks and development of differential subsidence [1 – 3]. In such conditions, the question of increasing the reliability on the thermal prediction the defrosting zones calculations of the PS is especially urgent. It is the heat calculation that is the determining factor in the choice of the tank foundation design [4].

Today, the problem of predicting the depth of defrosting zone is solved by numerical methods [5 – 7]. However, the time for solving such problems depends nonlinearly on the accuracy of the solution (cubic dependence for two-dimensional problems and 4-th power for three-dimensional problems when using explicit schemes of the method of finite differences). Besides, numerical methods do not take into account the unboundedness on the dimensions of the soil mass at the tank's base in connection with mathematical limitations. The latter circumstance leads to the appearance of boundary effects that distort the calculated temperature field near the boundaries of the computational domain (we mean the design area is a soil massif in which the thermal effect of the tank is felt). The process of finding the appropriate size of the computation area consists of the stages at its sequential increase. If at the next stage to increase the size of the calculated region the temperature ceases to change by a value greater than the maximum permissible error the required size of the computational domain is found, and the boundary effects are sufficiently small. The described process has the next significant disadvantage:

1. Requires significant time costs, increasing at each stage.

2. In conditions of a time deficit the search for the size of the soil body in specified path can lead to the selection of not optimal geometric parameters (we will mean optimal size of the soil in-situ is a size that provides a given accuracy of

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 17 (2017) pp. 7007-7010

solution with the smallest area).

This article is devoted to improving the methods of searching for the optimal size at the soil body. The following procedure allows us to find the optimal size of the soil in-situ emanate from the required accuracy of the solution.

RESEARCH METHOD

The simplest way to determine the magnitude of boundary effects is compare two solutions for one problem. In one solution, boundary effects are present, but in the other, there are none.

Firstly, we will find the solution of the problem in which boundary effects exist. The calculation scheme is shown in Figure 1.

In the general case, the process of changing the temperature regime at the base and the formation of defrosting zone is nonstationary. However, the greatest thermal effect on the MMG is achieved at the end of the life of the reservoir. By this time, the temperature regime stabilizes at the foundation soil and the boundary effects reach a maximum value. This allows us to solve the problem of determining the boundary effects in a stationary formulation on the basis of the linear differential heat equation in a cylindrical coordinate system (Laplace equation):

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} = 0 \quad (1)$$

The boundary conditions for the design scheme in Figure 1:

$$\left.\frac{\partial V}{\partial z}\right|_{z=H} = 0, \quad (2)$$

$$\left.\frac{\partial V}{\partial r}\right|_{r=R} = 0, \quad (3)$$

$$V = \begin{cases} T_{tank}, & r < P \\ 0, & r > P \end{cases}. \quad (4)$$

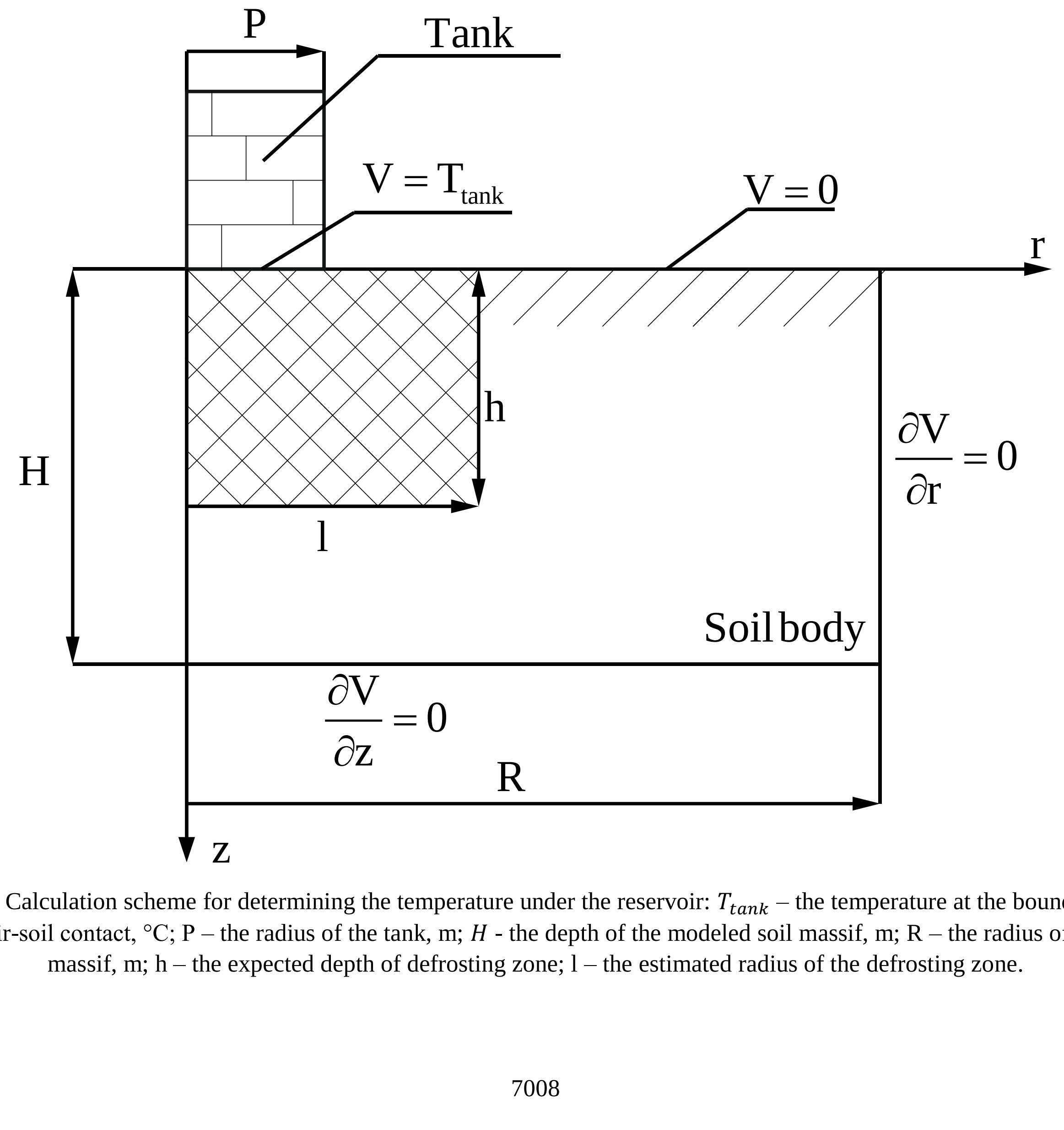

Figure 1: Calculation scheme for determining the temperature under the reservoir: T_{tank} – the temperature at the boundary of the reservoir-soil contact, °C; P – the radius of the tank, m; H - the depth of the modeled soil massif, m; R – the radius of the soil massif, m; h – the expected depth of defrosting zone; l – the estimated radius of the defrosting zone.

The solution for the case under consideration is well known. It is a Fourier-Bessel series [8]:

$$V_1 = T_{tank}\frac{P^2}{R^2} +$$

$$+\sum_{n=1}^{\infty} T_{tank}\frac{2PJ_1(a_n^1 P/R)J_0(a_n^1 r/R)cosh(a_n^1(H-z)/R)}{a_n^1 R\left(J_0(a_n^1 r/R)\right)^2 cosh(a_n^1 H/R)}, \quad (5)$$

where $J_\nu(x)$ – the Bessel function is the function of the first kind, of the ν-th order, of the real argument; a_n^ν- n-th positive root of the Bessel function of the first kind, of the ν-th order, of the real argument.

We obtained expression (5-6), for the temperature in a limited cylindrical massif of soil with a warm reservoir on the surface. Now we need to solve the same problem for an unrestricted array of soil ($R \to \infty$, $H \to \infty$), i.e. for the case with no boundary effects. For this, we apply the theory of Green's functions for a half-space $z > 0$, in a cylindrical coordinate system [9], taking into account the axial symmetry of the problem and the boundary condition (4):

$$V_2 = T_{tank}\frac{z}{2\pi}\int_0^{2\pi} d\varphi_0 \int_0^P \frac{r_0 dr_0}{(r_0^2+r^2-2rr_0 cos(\varphi_0)+z^2)^{3/2}}. \quad (6)$$

Now, when formulas are known that determine the temperature distribution for both the case with boundary effects (5) and without them (6), one can calculate their normalized difference, which will represent the normalized value of the boundary effects:

$$\Delta W = |V_2 - V_1|/T_{tank} \quad (7)$$

Figure 2 shows a graph of the normalized value of the boundary effects, calculated from formulas (5-7).

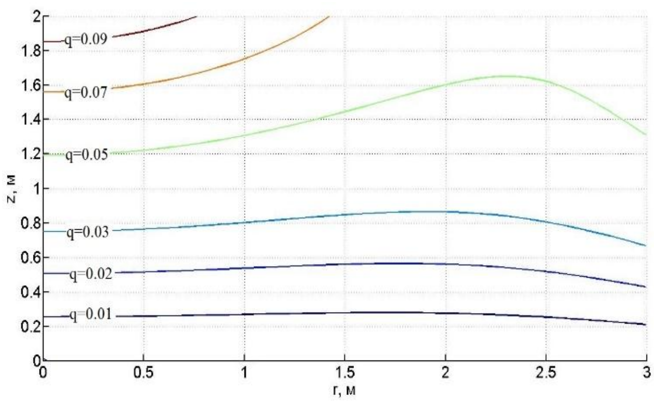

Figure 2: Isolines of value. The calculation was carried out for the case H = 2 m, R = 3 m, P = 1 m.

From the graph, a characteristic feature of boundary effects is visible: on the ground, they are absent, because the boundary conditions of the first kind (4) is coincide. At the same time, the boundary effects increase monotonically, when the depth increase too, and achieved the maximum at the maximal depth.

With the use of formulas (5-7), nomograms and methods were compiled that allow finding the optimal size of the computational domain, based on the required accuracy of calculation and the expected depth of defrosting zone. The following is the sequence of the reader's actions when using the proposed technique:

1. Collection of native data:

ΔT_{max} - the necessary accuracy of solution, ℃;

T_{tank} - the module of the temperature difference between the assets and the soil temperature at the depth of zero annual amplitudes, ℃;

h_{max} – the maximum depth on which it is necessary to provide the specified accuracy of the solution ΔT_{max} (it corresponds to the expected depth of the defrosting zone), m;

l_{max} – the maximum radius on which it is necessary to provide the specified accuracy of the solution ΔT_{max} (it corresponds to the expected radius of the defrosting zone), m;

P - the radius of the tank, m.

2. Calculation of dimensionless quantities:

$q = \frac{\Delta T_{max}}{T_{tank}}$ - the reduced accuracy of calculation;

$h = \frac{h_{max}}{P}$ - the reduced maximum depth at which the specified accuracy of the solution q is to be ensured.

$l = \frac{l_{max}}{P}$ – - the reduced maximum radius at which the specified accuracy of the solution q is to be ensured.

3. The finding the dimensionless minimum depth of the soil mass H: nomographs use (Figures 3-5), they are necessary to find the values of h, l and q. The perpendicular puts from the h axis vertically upwards, it is necessary to find the point of intersection with the isoline q. A perpendicular is left from the founded point to the intersection with the axis $ln\,H$.

4. The calculation of the absolute depth of the soil: $H_{abs} = P \cdot H$ – the minimum depth of the soil massif that will provide the specified accuracy of the solution to equation ΔT_{max}, m.

5. The determination of the optimum radius of the soil massif:

$$L_{abs} = P \cdot H\left(1.15\left(\frac{0.6714}{H}\right)^{1.75} + 1.3266\right) \quad (11)$$

Formula (11) allows us to find the optimum radius of the soil mass. It is valid in the range $H \in [0.7; +\infty]$.

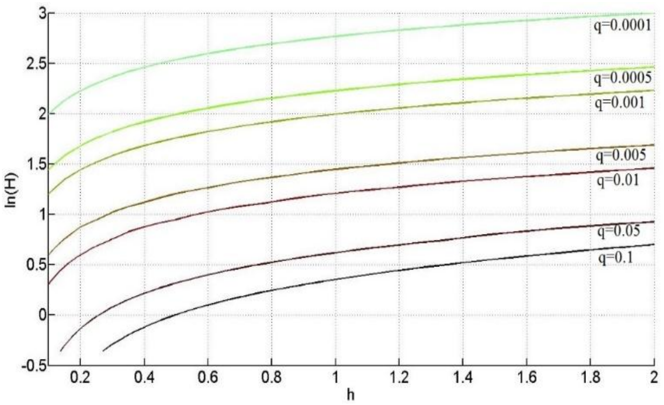

Figure 3: A nomogram for determining the optimal depth of the computational domain H for the case $h \in [0{,}1; 2]$, $l = 1$

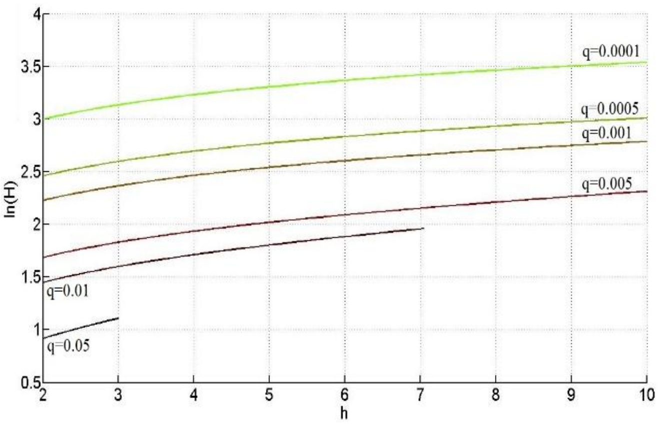

Figure 4: A nomogram for determining the optimal depth of the computational domain H for the case $h \in [2; 10]$, $l = 1$

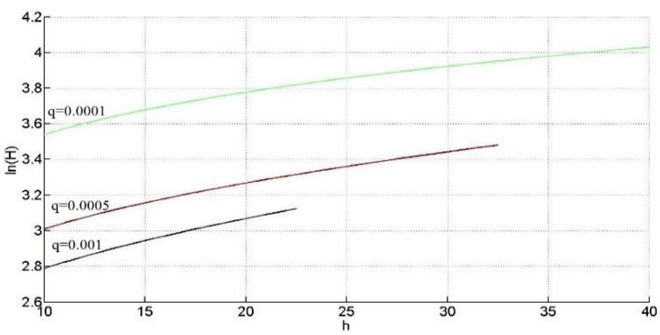

Figure 5: A nomogram for determining the optimal depth of the computational domain H for the case $h \in [10; 40]$, $l = 1$

CONCLUSION

Analytic expressions for the distribution of temperature under the reservoir in a homogeneous bounded and unrestricted soil massifs with allowance for rotational symmetry are found. The values of the boundary effects are calculated. Then were compiled the nomograms and methods for determine the optimal depth of the calculated area, which depend on the required accuracy of the solution and the expected depth and radius of the defrosting zone. A formula is obtained for calculating the optimal radius of the soil mass at a known depth.

REFERENCES

[1] Kushnir S.Ya., Pulynikov S.A., Malyushin N.A., Karnauhov M.Yu. (2012). Prostranstvennaja ustojchivost' podzemnyh magistral'nyh truboprovodov [Spatial stability of underground main pipelines]. Problemy sbora, podgotovki i transporta nefti i nefteproduktov. No. 1, pp. 51-56.

[2] Kushnir S.Ya., Pulnikov S.A., Serebrennikov A.A., Seniv D.M. (2010). Ustojchivost' prizm obvalovanija podzemnyh magistral'nyh neftegazoprovodov [Stability of prisms of boning of underground main oil and gas pipelines]. Izvestija vysshih uchebnyh zavedenij. Neft i gaz. No. 4, pp. 65-70.

[3] Kushnir S.Ya., Pulynikov S.A., Sysoev Yu.S., Seniv D.M. (2011). Analiticheskaja zadacha opredelenija udlinenija gazoprovoda v oblasti arkoobrazovanija [Analytical problem of elongation of the gas pipeline in the field of arcuation]//Problemy sbora, podgotovki i transporta nefti i nefteproduktov. No. 1, pp. 74-80.

[4] Ivanov I.A., Kushnir S.Ya. Magistral'nye truboprovody v rayonakh glubokogo sezonnogo promerzaniya puchinistykh gruntov [Pipelines in the areas of deep seasonal freezing of heaving soils]. SPb: OOO «Nedra» 2010: 174.

[5] Sergey A. Pulnikov, Evgeniy V. Markov, Yuri S. Sysoev and Natalia V. Kazakova. Optimization of Thermal Calculation of Buildings on Permafrost Soils to Reduce Boundary Effects. International Journal of Applied Engineering Research 2016: 24: 11877-11882.

[6] Sergey A. Pulnikov, Evgeniy V. Markov, Yuri S. Sysoev and Natalia V. Kazakova. Development of a Mathematical Model of the Diffusion-Filtration Mass Transfer in a Porous Plastically Deformable Medium. International Journal of Applied Engineering Research 2016: 24: 11883-11887.

[7] Evgeniy V. Markov, Sergey A. Pulnikov, Yuri S. Sysoev and Aleksandr D. Gerber. Development of Mathematical Model of Heat and Mass Transfer in Soil, with Provision for Gradients of Soil-Water and Soil-Salt Potentials. Part 1. International Journal of Applied Engineering Research. 2017: 12: 4340-4344.

[8] Carslaw H., Jaeger J.,Teploprovodnost' tverdyh tel [Thermal conductivity of solids]. M.: Nauka 1964

[9] Aramanovich I.G., Levin V.I., Uravneniya matimaticheskoy phisiki [Equations of mathematical physics]. M.: Nauka 1969.