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RELIABILITY OF BASEMENTS AND STRUCTURES IN CRYOLITHOZONE

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NEW FOUNDATION FOR STRUCTURES IN THE ARCTIC

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The paper describes a novel slab-on-grade foundation (floating foundation) which simultaneously performs three functions: transferring load of structures into the soils; reducing the permafrost temperature at the base of structures, increasing thereby the bearing capacity of soils they sit upon; and maintaining the required positive air temperature in the ground floor of the structure. These are achieved by introducing a heat pump into the foundation design. The considered foundation has significant advantages over the pile foundations widely applicable in the Arctic and provides for: independence from climatic conditions; low capital expenditures; multiple use.

Slab-on-grade foundation, permafrost, artificial cooling of the structure base, structure heating, heat pump, capital expenditures, climatic conditions

INTRODUCTION

The forthcoming extensive development of the Arctic resources will require using innovative construction technologies and pioneering new materials, which compared to conventional, will ensure high structural integrity, less weight, energy-saving technologies and environmental safety. The foundation construction on permafrost is particularly topical due to a lack of coarse grit soils allowing to use them as backfill material for the foundation bed.

Most of the buildings and structures constructed on permafrost are therefore built on pile foundations, which significantly increases construction time and costs. Given that when degradation of permafrost occurs such buildings can suffer distress or damage, crawlspaces (ventilated air space) need to be enclosed, which however, precludes the transfer of heavy loads on the structure's floor, and makes this technology increasingly low cost-effective due to its excessive materials consumption and the need for costly building heating systems. Note that metal, being is the basic material for piles and elements of crawlspaces, is commonly delivered on-site by air and is therefore listed among scarce goods. In addition, the installation of piles takes a long time and is largely associated with ecosystem disturbance and environmental issues in the wake.

The authors set out to minimize the above drawbacks in foundation design and construction technologies. In 2015, their efforts resulted in developing the design and calculation method for the slab-on-grade foundation, which does not require using coarse grit ground as backfill material. At this, reliably retaining the frozen state of the soil base (bearing medium) and allowing heating the building with low energy costs during the entire period of its operation [*Khrustalev et al., 2016*]. These design characteristics of the foundation were achieved by coupling it with a heat pump (HP).

DESCRIPTION OF DESIGN

The foundation, in itself, is a reinforced concrete slab consisting of two modules, with the upper incorporating a coil tube of the heating loop of HP (filled with water at temperature t_1), and the lower – enclosing a pipe coil of the cooling loop of HP (filled with anti-freezing liquid at temperature t_2). The span between the loops is filled with a thermal insulation material Penoplex with thermal resistance R_b. The upper pipe coil is intended to heat the indoor space in the ground floor of the building, while the lower ensures artificial refrigeration of the soil base. At this, two turns of the coil protrude beyond the outer wall of the building, which precludes thawing of soil beneath the edge of the building during the summer season.

As such, the foundation simultaneously performs three functions: 1) it transfers the load of the building to the base; 2) it lowers the temperature of permafrost underneath the building and thereby increases its reliability as the soil base; 3) it maintains the required positive air temperature inside the building (in a ground floor). The slabs-on-grade foundation consists of precast concrete blocks, which in on-site conditions are braced together using the welded embedded fittings and are connected parallel to the HP, which allows minimize the hydraulic losses in the loops.

The slabs-on-grade foundation is installed on perennially frozen soils (permafrost) in the second half of winter after the freezeback of seasonal thaw (active layer). The end sides of the slab foundation are earthed-up with local material. It is advantageous that the concrete modules can be site-precast during the summer (which is recommended) and transported on sled platforms in winter, to the construction site. The HP connected to the slab foundation operates continuously, inasmuch as the heating season in the Arctic lasts year round, and therefore provides for heating of the building and artificial cooling of the soil base permanently. The operation scheme of the heat pump is shown in Fig. 1.

As follows from the scheme, the heat applied to heating the building Q_3 is taken up from the ground by the cooling loop of HP; simultaneously with it, to the cooling loop heat Q_2 comes from the heating loop of HP. Both these fluxes are directed into the refrigeration unit of HP, where the heat energy from a low-potential source (low-potential heat) is converted into high-potential heat energy [*Fortov, 2012*], which is summed up with the energy loss at the compressor of refrigeration unit:

$$(Q_2 + Q_3)/(COP - 1).$$

Conversion coefficient *COP* is derived from formula [*Novikov, 1984*]

$$COP = 0.5\frac{t_1 + 273 + 3}{t_1 + 3 - (t_2 - 3)}, \qquad (1)$$

where t_1, t_2 is temperature in the heating and cooling loops of HP, °C. Once these heat fluxes arrive at the heating loop of HP, one part Q_1 is directed to the building as the floor heating agent, while part Q_2 returns to the cooling loop. This cycle is set to be repeated in the future. The heat fluxes are controlled by the following parameters: water temperature t_1 in the heating loop, and antifreeze t_2 in the cooling loop of HP and thermal resistance R_b between the loops. These should be selected in such a way that Q_1 is does not exceed the sum of $Q_3 + (Q_2 + Q_3)/COP$ and is to be not less than 50 W per 1 m^2 of the floor of the building during the coldest five days. This approach is further explained by a calculation example below.

CALCULATION EXAMPLE

Basic engineering design initial data. Single-storey public building built from structural skeleton on frozen soils, with the cooling system and floors heated by heat pump. The service life of the building is 25 years. The building size in the plan view is 25 × 40 m, its area is $S = 1000$ m^2. The foundation for such a building will consist of 26 precast concrete slabs (modules) 3.1 × 12.5 m in size in plan view; the module area is $S_m = 38.75$ m^2. The temperature inside the building is $t_{in} = 20$ °C.

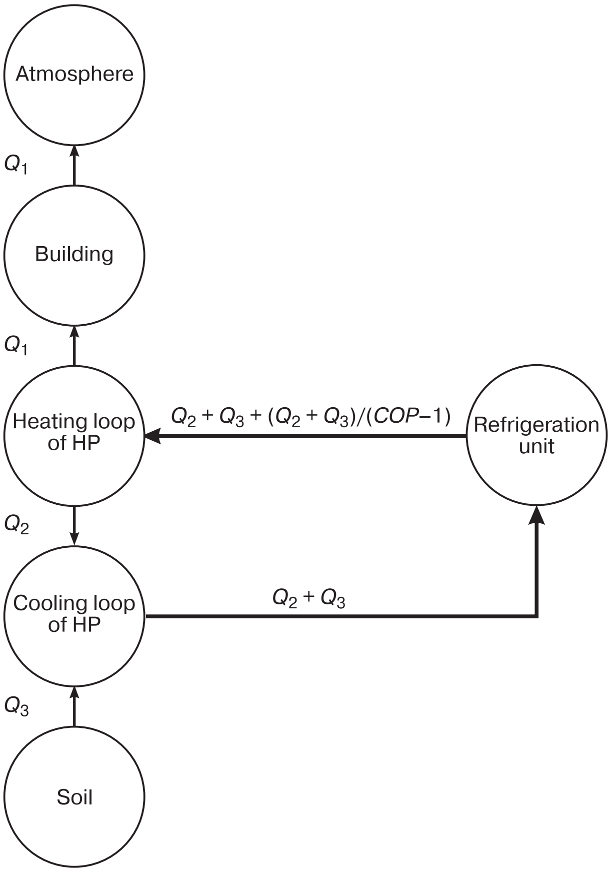

Fig. 1. Heat exchange scheme of heat pump connected to slab-on-grade foundation.

See main text for notation.

The intensity of maximum heat loss from the building during the heating period is $Q_b = 50$ kW. The duration of the heating period $\tau_w = 12$ months = = 8760 h. The underlying permafrost temperature is $t_0 = -5.5$ °C. The precast slab foundation module is a reinforced concrete slab (Fig. 2) with built-in heating

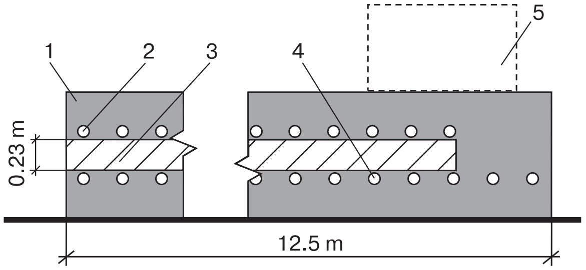

Fig. 2. Longitudinal cross section of precast concrete foundation module.

1 – reinforced-concrete frame of foundation; 2 – pipe coil of the heating loop of HP; 3 – thermal insulator (Penoplex); 4 – pipe coil of the cooling loop of HP; 5 – position of the outer wall of the building.

and cooling loops of HP as a system of PE pipe coils spaced at s = 0.15 m. The outer diameter is $d_{\text{out}} = 0.06$ m; the internal diameter is $d_{\text{in}} = 0.054$ m. The length of pipes of the cooling/heating loops incorporated into one precast slab floor module is 251 m, which includes 38 quarter-turn (1/4) actuators. The span between the loops is filled with heat-insulating material with thermal resistivity $R_b = 0.278$ m^2·°C/W.

In the plan view, the foundation modules are arranged in two rows allowing parallel connection with the HP using two modular manifolds (each is 220 m in length, and includes 4 quarter-turn (1/4) actuators) (Fig. 3). The outer diameter of the modular manifolds $d^{\text{k}}_{\text{out}} = 0.0885$ m, internal dia. $d^{\text{k}}_{\text{in}} = 0.0805$ m. The heating loop uses water, while cooling unit is filled with antifreeze (20 % water solution ethylene glycol which freezes at a temperature below its cooling temperature in the thermosyphon evaporator). The fluid temperatures in the loops are t_1 = +40 °C and t_2 = –10 °C, respectively. Geographically, the climate and soil conditions correspond to the area occupied by rotational village Sabetta on the Yamal Peninsula.

Thermal calculation of the slab-on-grade foundation. The calculation was carried out by the mathematical modeling (using QFrost software [*Pesotskii, 2016*]) of thermal interactions of the slab foundation with the building and the underlying permafrost. The calculation results are as given below: time of operation of HP is 25 years; water temperature in the heating loop is t_1 = 40 °C; antifreeze temperature of in the cooling loop is t_2 = –10 °C; thermal resistivity measured between the loops is $R_b = 0.278$ m^2·°C/W; heat flux intensity: Q_1 = 67.94 kW (from the heating loop to the building and from the building to the atmosphere), Q_2 = 128.57 kW (from the heating loop to the cooling loop), Q_3 = 2.58 kW (from permafrost to the cooling loop); $Q_3 + (Q_2 + Q_3)/(COP - 1) = 74.64$ kW (where COP is conversion coefficient, see the formula (1)).

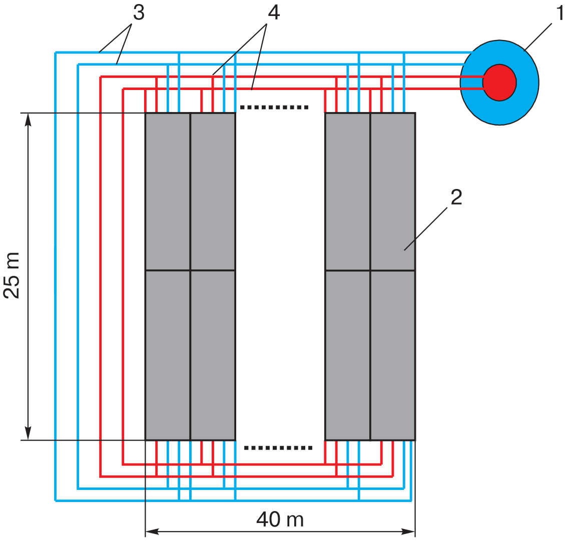

Fig. 3. Diagram for the precast foundation modules connection to the heat pump.

1 – heat pump; 2 – precast concrete foundation module; 3 – modular manifold of the heating loop of HP; 4 –modular manifold of cooling loop of HP.

These data allowed us to infer that the heat supplied by HP is only slightly in excess of the rated minimum of 50 kW for this building, which indicates the adequacy of the chosen control parameters t_1, t_2 and R_b.

The heating capacity of the heat pump (HP) will be equal to $N_T = Q_2 + Q_3 + (Q_2 + Q_3)/(COP - 1) = 128.57 + 2.58 + (128.57 + 2.58)/(2.82 - 1) \approx 203.2$ kW. The conversion coefficient is calculated using formula (1):

$$COP = 0.5\frac{t_1 + 273 + 3}{t_1 + 3 - (t_2 - 3)} = 2.82.$$

The required amount of electric power is: $N_E = (Q_2 + Q_3)/(COP - 1) = (128.57 + 2.58)/(2.82 - 1) \approx 72.1$ kW.

Besides, the simulation results have shown that throughout the service life of the slab-on-grade foundation, seasonal thaw propagation beneath the foundation base will be completely excluded, allowing the foundation to permanently rest on the hard-frozen ground, practically not affected by compressibility (in the absence of consolidation of frozen soils) (Fig. 4).

Hydraulic calculations of heating and cooling contours loops. The calculation determined the fluid flow rates and pressure losses in the loops: as W_1 and h_1 for water, and as W_2 and h_2 for antifreeze, respectively. The fluid flow rate (water, antifreeze) in the loops is derived from the formula:

$$W_{1,2} = \frac{N_T}{C_{1,2}\Delta t},$$

where $W_{1,2}$ is fluid consumption, m^3/h; N_T is rated heat capacity of HP, W; $C_{1,2}$ are fluid heat capacities,

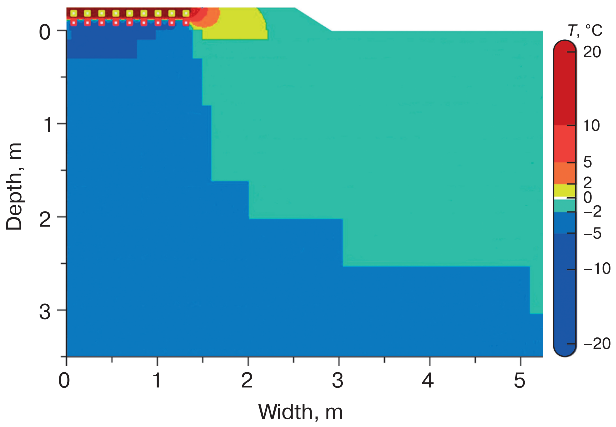

Fig. 4. Temperature field at the base of structure after 25 years of operation life of the structure.

W·h/(m^3·°C); Δt is in/out fluid temperature difference (equals 5 °C).

Knowing the fluid flow rate, we determine the speed of its movement in each segment of the loops and the pressure loss along them. The calculation was carried out according to well-known formulas (e.g., [*Bolshakov, 1972*]). Skipping the procedure here, the final calculation results are given in Table 1. Based of the above thermal and hydraulic calculations, we select the heat pump according to the following parameters: rated heat capacity (203.2 kW); electric power consumption (72.1 kW); water consumption in the heating loop (40.64 m^3/h); pressure loss in the heating loop (3.05 m, for water column); antifreeze consumption in the cooling circuit (36.58 m^3/h); pressure loss in the cooling loop (3.91 m, for water column).

These requirements for rated heat capacity can be met by Heat Pump CR-230xB.

(Its cost is 1,604,460 rubles).

Mechanical interaction between the slab-on-grade foundation and perennially frozen soils base. The slab-on-grade foundation for a single-storey public building built from skeletal frame experiences rather low loads from the weight of the building, equipment and people. In this case, the foundation slab rests on a virtually incompressible soil base, and therefore, the slab reinforcement can be minimal and is to be determined proceeding only from the conditions for its installation and possible replacements.

Table 1. **Results of hydraulic calculation**

Parameter	Heating loop	Cooling loop
Total fluid consumption in the contour, m^3/h	40.64	36.58
Total fluid consumption in the pipe coil of foundation slab, m^3/h	1.56	1.41
Fluid velocity in the pipe coil, m/s	0.19	0.17
Pressure loss in the pipe coil, m	0.33	0.31
Pressure loss in the modular manifold, m	3.05	3.91
Total pressure loss in the loop, m	3.05	3.91

COST EFFECTIVENESS ANALYSIS OF THE UTILIZATION OF SLAB-ON-GRADE FOUNDATION

The economic effect analysis is based on the comparison between the above discussed two options (variants) for the building construction (Sabetta village, Yamal Peninsula): Variant 1 – with a heat pump; and Variant 2 – with the cooling system which requires enclosing a ventilated air space under the building (Fig. 5). Variant 1 (slab-on-grade foundation) construction: building is erected directly on the frozen soils surface with the concrete slab sides earthed-up by material readily available at the site (earth backfill). Variant 2 (pile foundation) construction: building is constructed on a pile foundation using metal piles 219 × 8 mm in diameter (length: 1944 m) and a diameter of 159 × 8 mm (length: 2093 m). A reinfor-

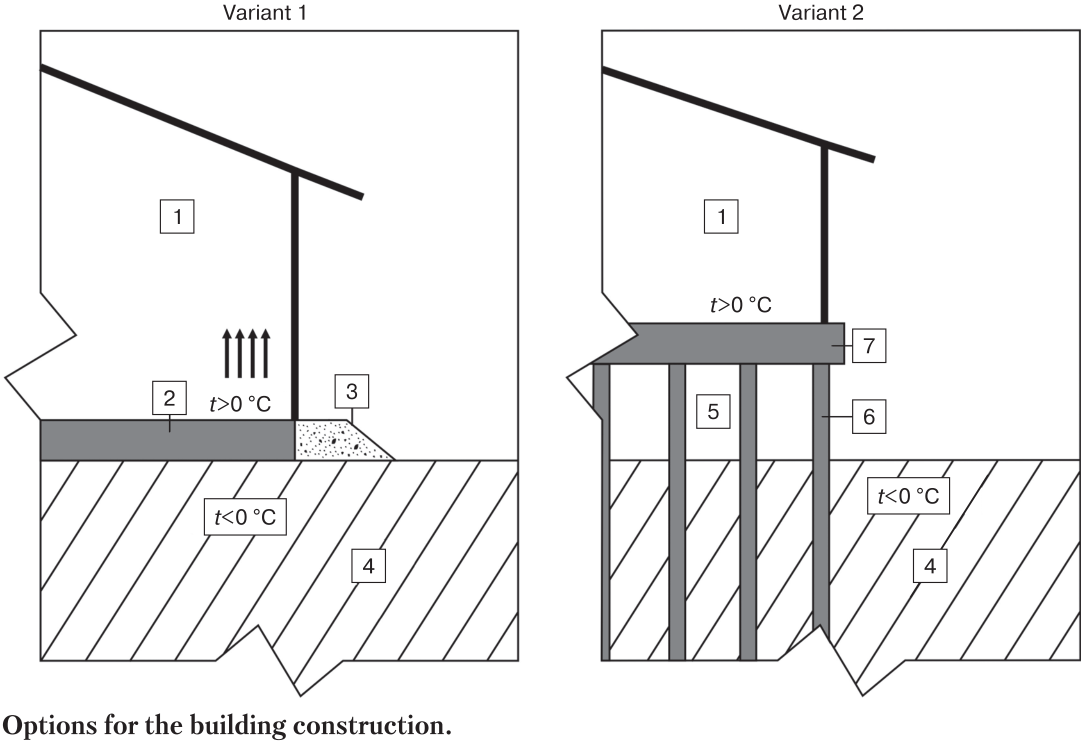

Fig. 5. Options for the building construction.

1 – building; 2 – slab-on-grade foundation; 3 – earth fill; 4 – frozen soil base; 5 – ventilated air space (crawlspace); 6 – pile foundation; 7 – reinforced concrete frame (Rostwerk) and insulation.

ced concrete frame (Rostwerk) overlying pile-heads is meant to hold the reinforced concrete slab of ventilated air space (crawlspace). The reinforced concrete volume in the Rostwerk and concrete slab is 100 m^3. The cost calculations were made in keeping with the BPRGD (SBtsP) 81-2001-03 rules and regulations (Buildings and Civil Housing Objects) [*2010*].

The cost effectiveness is estimated using the formulas below, either

$$E = D_2 - D_1, \tag{2}$$

or

$$E_w = \frac{D_2 - D_1}{D_2} \cdot 100\,\%,$$

where D_1, D_2 – operating expenditures for Variants 1 and 2, rb./yr (alternatively, %), individually calculated as:

$$\begin{aligned} D_1 &= pK_1 + P_E Q_1, \\ D_2 &= pK_2 + \frac{P_E}{m} Q_2, \end{aligned} \tag{3}$$

where p is bank loan redemption rate, 0.12 yr^{-1}; K_1, K_2 is total invested capital for Variants 1 and 2, rb.; P_E – electricity rate (tariffs), 0.82 rb./kW·h; m is the electricity to heating energy tariffs ratio; Q_1, Q_2 is the building heat consumption values for Variants 1 and 2, kW·h;

$$\begin{aligned} Q_1 &= (Q_2 + Q_3)t_y/(COP - 1), \\ Q_2 &= (Q_3 + (Q_2 + Q_3)/(COP - 1))t_y \end{aligned} \tag{4}$$

(t_y is duration of the year, h). The total invested capital for Variants 1 and 2 are calculated as below:

$$\begin{aligned} K_1 &= D_1^f + D_1^w + D_1^c + D_{\mathrm{HP}}, \\ K_2 &= D_2^f + D_2^w + D_2^c, \end{aligned} \tag{5}$$

where $D_{1,2}^f$, $D_{1,2}^w$, $D_{1,2}^c$ are costs of construction of the foundations, heating and cooling systems for Variants 1 and 2, rb.; D_{HP} is cost of heat pump, rb.

$$\begin{aligned} D_1^f &= c_{fc}V_{fc1} + c_{gr}V_{gr1}, \\ D_2^f &= c_{fc}V_{fc2} + c_p G_p + c_{pp} n_p + C_t, \end{aligned} \tag{6}$$

where c_{fc} is cost of reinforced concrete in use, 6,723 rb./m^3; c_{gr} is cost of local materials in use, 550 rb./m^3; V_{fc1}, V_{gr1} is the volume of foundation and backfill material, m^3; V_{fc2} is volume of reinforced concrete rostwerk and slab, m^3; c_p is cost of 1 t pile, rb./t; c_{pp} is cost of piling, rb./pcs.; C_t is cost of the on-site pile testing, rb.; G_p is total weight of piles in position, t; n_p is the number of piles in position, pcs.

$$\begin{aligned} D_1^w &= c_{pt}L + c_{is}V_{is1}, \\ D_2^w &= c_w S + c_{is}V_{is2}, \end{aligned} \tag{7}$$

where c_{pt} is cost of polymer pipe in use, 180 rb./m; c_{is} is cost of insulation material in use, 4,861 rb./m^3; c_w is cost of heating system calculated per 1 m^2 of the floor, rb./m^2; L is length of pipes of the heating loop of HP, m; V_{is} is volume of insulation, m^3; S is total area of the building floor, m^2.

$$D_1^c = c_{pt}L, \tag{8}$$

where L is the length of pipes of the cooling loop, m.

The volume of backfill material required for the slab-on-grade foundation earthing-up is estimated using the formula:

$$V_{pf} = h_{pf}\,(2 + 1.5h_{pf})(B_{bl} + L_{bl} + 2 + 1.5h_{pf}), \tag{9}$$

where B_{bl} is the building width, 25 m; L_{bl} is the building length, 40 m; h_{pf} is height of the slab-on-grade foundation, 0.23 m.

Table 2. **Cost effectiveness analysis of utilization of slab-on-grade foundation**

Description of costs	Variant 1			Variant 2		
	Price, rb.	Quantity	Cost, rb.	Price, rb.	Quantity	Cost, rb.
Foundation						
RC (reinforced concrete)	6723 (per 1 m^3)	193.1 m^3	1 298 211	6723 (per 1 m^3)	100 m^3	672 300
earth backfill	550 (per 1 m^3)	23.81 m^3	13 093	–	–	–
piles Φ219x8 mm	–	–	–	45 595 (per 1 t)	80.93 t	3 690 000
piles Φ159x8 mm	–	–	–	36 400 (per 1 t)	62.36 t	2 270 000
pile testing	–	–	–	17 441.9	344	6 000 000
Heating unit						
pipes	180 (per 1 m)	381 m	68 580	3000 (per 1 m^2)	1000 m^2	3 000 000
insulation	4861 (per 1 m^3)	9.73 m^3	47 297	4861 (per 1 m^3)	87.5 m^3	425 338
Cooling unit						
pipes	180 (per 1 m)	381 m	68 580	–	–	–
Heat pump	1 604 460	1 pce.	1 604 460	–	–	–
Total invested capital			3 100 221			16 057 638
Operating expenditures over one year			889 651			2 092 397

The results of calculations using formulas (3)–(9) are given in Table 2.

The data listed in Table 2 allowed an inference about the slab-on-grade foundation coupled with a heat pump resulting in considerable savings: 80.7 % for capital investments and 57.5 % for operating expenditures. Plus, the surplus of construction time saved in the case of slab-on-grade foundation as compared to pile foundation.

CONCLUSION

The slab-on-grade foundation combined with the heat pump has a number of significant advantages in comparison with the pile foundation commonly used in structure/building construction in the Arctic. These include:

– its ability to simultaneously perform three functions of: transferring the load from the building to the soil base; lowering permafrost temperature in soil base; retaining the required positive room temperature in the first floor of the building;

– negligible impact from weather;

– easy module-to-module installation;

– lower construction time.

A large-scale implementation of this novel construction technique will largely contribute to the advancement of region-specific, environment-friendly construction technologies into the Arctic.

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