CONSTRUCTION EXPERIENCE ON HYDRAULIC FILL IN A PERMAFROST AREA

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Abstract

A unique experiment to use hydraulic excavation to produce artificial hydraulic fill for a construction site on permafrost, was undertaken in Yakutsk. The results of experiments and instrumental observations have established the following:

- the impact of the hydrological and temperature regime of the Lena River on the ground-water level;
- the influence of the hydraulic fill on the underlying permafrost;
- the common tendencies of development of thermal processes in permafrost and the hydraulic ground fill;
- the behaviour of structures built on the artificial ground fill.

The data obtained allowed the formulation of major design principles, to deduce formulas of calculation of the underflooding zone and foundation settlements. The accumulated experience showed the efficiency of construction sites prepared by hydraulic methods in northern regions.

Introduction

The application of hydraulic excavation to produce artificial ground fill on permafrost has characteristics that differ from the same activity in non-permafrost areas due to disturbance of the thermal and moisture regimes of natural deposits. A three-layer soil base forms after hydraulic filling, which is made up of the unfrozen hydraulic fill, the thawed natural ground, and the underlying permafrost. Moreover, the low average annual air temperatures and permafrost lead to freezing of the thawed layers. The development of cryogenic processes and the behaviour of the fill depend on many factors: composition and thickness of the hydraulic fill, technology and season of hydraulic excavation works, type, thickness, compressibility and the rate of consolidation of the thawed soils, the temperature of the permafrost, the thermal balance characteristics of the fill surface, the hydro-geological regime of the newly produced surface, and the climatic parameters of the region.

Study site

More than 10 years’ experience of construction and operation of buildings on artificial hydraulic fill has been accumulated at a site in Yakutsk.

Natural soils within the active layer are composed of silty sands, sandy loams and clay loams with peat and silt inclusions. Sandy permafrost is present to depths of 16-20 m (both silty and medium size); below, Jurassic deposits occur: aleurites, aleurolites and sandstones. Before hydraulic filling, the area was subjected to annual flooding. Ground temperatures at the depth of zero annual amplitude (10 m) were -0.3 to -0.8°C.

Hydraulic sand fill was produced during the summers of 1979-1982 from deposits in the Lena River. The thickness of the fill was from 6 to 12 m. Data on the physical and mechanical properties of the hydraulic sand fill and the underlying ground, obtained from field and laboratory tests, are given in Table 1.
Thawing of underlying natural ground under thermal impact of the fill was very intensive after the first stage of hydraulic filling. Then the depth of thaw became stable at a depth of 4 - 5 m below the original surface. The hydraulic fill gradually drained. The ground-water table became the same as in the river. Three layers occurred in the hydraulic sand fill which differed in terms of degree of saturation. In the upper layer, the moisture content was close to molecular moisture capacity (0.03 - 0.05). In the second layer with a thickness of about 0.5 m, moisture was due to capillary rise (0.1 - 0.15). The third layer, located below the ground water level, had a moisture content close to saturation (0.22 - 0.26).

<table>
<thead>
<tr>
<th>Soil classification</th>
<th>Depth *</th>
<th>Particle density g/cm³</th>
<th>Ground density g/cm³</th>
<th>Moisture content %</th>
<th>Thawing coefficient MPa</th>
<th>Compression coefficient MPa⁻¹</th>
<th>Modulus of deformation MPa</th>
<th>Coefficient of filtration m/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro sand fill</td>
<td>3.4</td>
<td>2.66</td>
<td>1.58</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>13.5</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>2.66</td>
<td>1.6</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>19.5</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>6.8</td>
<td>2.66</td>
<td>1.64</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>21.0</td>
<td>5</td>
</tr>
<tr>
<td>Silty sand with vegetation remnants</td>
<td>1.0</td>
<td>2.74</td>
<td>1.7</td>
<td>30</td>
<td>0.037</td>
<td>0.41</td>
<td>-</td>
<td>0.067</td>
</tr>
<tr>
<td>Peat silty loam</td>
<td>2.3</td>
<td>2.68</td>
<td>1.59</td>
<td>54</td>
<td>0.05</td>
<td>0.8</td>
<td>-</td>
<td>0.15</td>
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<tr>
<td>Medium grained sand</td>
<td>4.10</td>
<td>2.66</td>
<td>1.77</td>
<td>22</td>
<td>0.022</td>
<td>0.24</td>
<td>-</td>
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<tr>
<td>Fine grained sand</td>
<td>11</td>
<td>2.64</td>
<td>1.94</td>
<td>26</td>
<td>0.028</td>
<td>0.285</td>
<td>-</td>
<td>0.16</td>
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<tr>
<td>Sandstone</td>
<td>12</td>
<td>2.72</td>
<td>2.01</td>
<td>17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Results of the experiment

GROUND-WATER LEVELS

Long-term observations of the influence of the Lena hydrological regime on the ground water level within the hydraulic sand fill showed that the flood zone in spring was 10 - 18 % larger than has been calculated for moderate climate conditions which is stipulated by the presence of permafrost. Calculated parameters of the depression curve with an increased coefficient of 1.15 - 1.2 are close to the observed ones which allows them to be applied to the other water levels in the river. Thus, if the expected flood of the Lena level is 1 % of provision, the penetration of the saturation zone inside the hydraulic sand fill calculated by the Polubarinova-Kochina formula (1977) with the correction coefficient is 171 m; if the provision is 50 %, the penetration is 121 m.

However, fluctuations of the ground-water table in relation to the river water-level occur not only within the flood zone but in virtually the entire hydraulic ground fill. This shows that there is a connection between the ground water of the underlying soil and the talik underlying the Lena River. According to observations from 1980-1994, the maximum level of ground water occurred in July. Then it stabilized with some fluctuations during summer normal water-levels and summer and fall floods.

With a drop of flood levels in the river, the gradient of water in the hydraulic fill develops towards the river. The ground water infiltrates both through the sides and the surface of the fill and through the talik zones of underlying soils.

It has also been established that hydraulic mechanized works at the neighbouring sites and leakages from mechanical systems also influenced the ground-water level. Thus, water-level rise occurred in all observation boreholes from the beginning until the end of hydraulic ground filling which took place from the middle of July until late October 1992. During this period, water filtration into the previously inwashed soil influenced its water content.

In 1993-1995 there was no excavation at the neighbouring sites. Regular leakages from sanitary and sewage systems significantly influenced the ground-water level, which was high and practically unchanged for a year.

It should be noted that the factors that influenced the ground-water level and temperature regime of the area occurred as a result of the infringement of engineering works and operation system rules.

FREEZING OF HYDRAULIC FILL

It is important to predict the development of cryogenic processes at the new site. These can be determined from the components of heat exchange between the fill surface and the atmosphere, the thickness of the snow cover, vegetation growth, infiltration of precipitation, ground properties and heat release from structures.

Figure 1. (a) Plan of location of (1) wall and (2) settlement marks, (3) temperature and (4) piezometric pipes at the base of experimental buildings, and (b) scheme of installation of settlement marks in the fill and underlying soil.
The results of such predictions, developed by experts of different organizations (Melnikov Permafrost Institute, Institute of Physical and Technical Problems of the North, SIBTSNIIS, MGU, LenZNIIEP) on the basis of a two-dimensional Stefan problem, showed that under the climatic conditions in Yakutsk, after hydraulic filling, a gradual freezing of thawed underlying and unfrozen hydraulic fill soils would occur, accompanied by a rise in the permafrost table towards the hydraulic fill. The depth of underlying soil thaw is almost independent of the technology of hydraulic works and of the thickness of fill, being on average 4 - 5 m on sandy sites, 3 m on clay sites and 2 m on sites, composed of peat. The rate of freezing is controlled by the thickness of fill, by the season and stages of work, and by the ground temperature and hydrogeological regime. For instance, if the underlying ground temperature is zero and a 6 meter hydraulic fill is produced in one stage, this block will freeze in 8.5 years, and it will take more than 10 years to freeze completely. Under lower temperature conditions (-1.9°C), the site will freeze completely in 7.5 years. Two-stage hydraulic filling shortens the freezing period. If the total moisture content of the hydraulic fill is 0.05, the entire freezing of a 7 meter block will take place in 6 years. The period of the permafrost formation increases for higher soil moisture contents. It will take about 35 years if the ground moisture content is 0.15. Should discontinuous water seepage occur within the thawed layer and the hydraulic fill, then according to the theory of Konstantinov et al. (1981) a discontinuous thawing of the underlying soil will be observed. All predictions showed that if there was no water seepage, permafrost formation occurs on the artificial area. This is proven by full-scale observations on the test site and by the experimental construction.

On the basis of the analyses, it was accepted that one solution to design buildings was to use air spaces, maintaining the freezing of thawed underlying ground or preserving its frozen state.

**Construction and Settlement**

Within this special project, three experimental buildings were designed and a special test site was selected. This project planned to use different types of foundations: piles, footings and slabs. However, it was impossible to drive piles into the hard hydraulic sand fill. Therefore the two experimental buildings were constructed on prefabricated footings consisting of three elements - slab, footing and column. The fill was produced in two stages. During the first stage, the fill reached the level of the foundation slab. Foundations were then installed with subsequent soil placement. The foundations of the first experimental building (1-B) were constructed during a year and a half after the beginning of hydraulic work, and the second building (1-A) in the three years after that.

The foundations of a third experimental building were designed according to recommendations and calculations of NIIOSP (Kutvitskaya, 1995) and involved the use of a solid slab at the depth of only 0.5 m, with one deformation and two expansion seams.
The sites of the experimental buildings and the test site at the construction site were supplied with temperature and piezometric pipes and with a cluster of survey marks for measuring ground settlement. Each cluster included five special marks installed at different depths of the hydraulic fill and of the underlying soils. Settlement marks were also located on the foundations (Figure 1).

The results of long-term observations of settlement and temperature regime showed the following.

Settlement of underlying ground occurred at the experimental site during the period from May 1980 until October 1995 as follows: the mark buried in the underlying ground at the depth of 0.5 m experienced 53.5 cm of settlement, while the mark buried at a depth of 2.5 m had 33.5 cm settlement. The foundation settlement of experimental building 1-B during the 13 years from September 1982 until October 1995 was 34.7 cm. The average settlement of building 1-A over a decade (from May 1985 until October 1995) was 14.3 cm. The magnitude of settlement of buildings constructed later was lower than foundation settlements of experimental buildings 1-A and 1-B. However, a regular trend in settlement with time was found and the settlement curves are similar (Figure 2). This proves that foundation settlements are controlled mainly by settlement of the underlying thawed ground and by compaction of the hydraulic fill. Additional settlement due to building loads is insignificant.

Full-scale observations of foundation settlements of the experimental building constructed on the slab foundation, showed that for 2.5 years after foundation installation, including the period of construction and putting it into operation, the average magnitude of building settlement was 3.0 cm, with a maximum of 3.5 cm, and a minimum of 2.5 cm.

The settlement data obtained provide valuable information on the prediction of deformation magnitudes. Comparison of the real settlements with predicted ones is shown in a paper by Roman et al. (1990). The total settlement of the building foundation can be calculated as the sum of settlements of individual layers formed by the hydraulic fill:

$$S = S_1 + S_2 + S_3 + S_4$$  \[1\]

where $S_1$ is the settlement of compressed layer under the stress of the foundation;

$S_2$ is the settlement of the underlying ground, thawed and compacted by the hydraulic fill;

$S_3$ is the settlement of hydraulic fill due to its self-compaction;

$S_4$ is the settlement of the permafrost due to additional ground thawing during construction, plus operation and compaction under the load of the above ground layers.

The magnitudes of the settlements were analysed according to standard procedures (SNIP 2.02.01 - 83 and SNIP 2.02.04. - 86).

As discussed above, the greatest settlement is $S_2$, the magnitude of which can be defined in accordance with the theory of seepage consolidation as deformation of a water-saturated non-draining soil layer, located on a non-compressible base and loaded by a filtration layer (SNIP, 1985). According to the settling mark data, it was found that the coefficient of filtration of underlying soils is 0.012 - 0.015 m/y, which is as much as 10 times less than the magnitudes obtained for natural deposits.

Measurements of ground temperatures in building foundations showed that under natural climatic conditions, freezing of thawed hydraulic fill occurs at rates close to the predicted values. Figure 3 shows the ground temperature changes with depth and time in the base of experimental building 1-B. A rise of the permafrost table occurred inside the hydraulic fill. Beneath

Figure 3. Ground temperature change with depth at different times below the base of buildings on the fill. 1 - natural ground surface; 2 - the surface of hydraulic fill; 3 - ground temperature profile in April, 1985; 4 - temperatures in November, 1986; 5 - temperatures in May, 1994; 6 - temperatures in October, 1995.
the active layer, which is 5 - 6 m for low moisture content hydraulic sand fill, the ground temperatures are close to the natural ones (i.e., -0.5 to -0.8°C).

Conclusions

Based on the data from the long-term research, a Departmental Building Code (Anonymous, 1988) has been developed for geological survey, design and construction on artificial hydraulic fill in Central Yakutia. This Code can be successfully used in other northern regions.

On the whole, the experience in Yakutsk has shown that hydraulic fill can be used to prepare a construction site in permafrost regions. It is recommended that the technology of hydraulic filling and construction is followed carefully, together with the requirements for operation of buildings and mechanical systems which should provide the formation of calculated temperature and moisture regime on the entire hydraulic fill and at the base of structures.

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References


