Reinforcement of strip foundations of old structures built on permafrost

A.N. Tseeva, O.I. Matveeva & A.E. Viktorov
Yakut Design Research Institute for Construction, Yakutsk, Russia

ABSTRACT: The first brick structure was built on permafrost in Yakutsk in 1707–1709. However, the construction approach for brick buildings on frozen ground did not differ from construction on unfrozen ground before the end of the first third of the 20th century; typically rubble stone strip foundations were laid at a depth of 2.5–3.0 m. Most of the buildings of that period are preserved, restored or reconstructed and are considered as historical monuments of architecture and engineering on permafrost. The analysis of ground conditions, conducted as part of an investigation into the serviceability of strip foundations, led to a change in the authors’ approach to foundation reinforcement. Primarily, the strip foundations were cemented or the foundations were increased in width. Depending on the ground conditions, micropiles were installed below the existing strip foundations. This paper presents specific engineering and geological conditions and the technical concepts adopted for foundation reinforcement design of old buildings on permafrost.

1 INTRODUCTION

Intensive construction of brick buildings on permafrost in the North of Russia began in the middle of the last century. There were few brick buildings on permafrost before that time (Voitkovsky et al. 1968). It was complicated to build and preserve such buildings because the underlying permafrost melted under the thermal effect of the structure, resulting in its deformation or destruction. Nevertheless, some buildings preserved in Yakutsk date back to the beginning of the 20th century, these now being considered as architectural monuments. Their restoration is of great importance, not only from the architectural view of the city, but also for the world community as examples of early preservation of buildings on permafrost.

Over the past few years, great attention has been paid to the restoration of architectural monuments in Yakutsk. The Nikolsky and Preobrazhen Churches have been restored already, whereas the National Library and the Real School of the National Art Museum are now under restoration.

All buildings have been constructed in the traditional style of that period, i.e. rubble-work strip foundations with a depth of between 2.5–3.0 m. The state of the buildings and the existing frozen ground conditions require the reinforcement of foundations. This paper presents a description of the technologies that were used for the first time, or designed for strip foundation strengthening in the cryolithozone.

2 BASIC INFORMATION ON BUILDINGS

The Pushkin National Library building was constructed in 1911 according to the design of K.A. Leshevich. In the course of construction, no devices were envisaged and no measures were taken to maintain the frozen ground conditions. As a result, the building had begun to deform by 1925, requiring the following works to be conducted from 1939 through to 1941, and which were to be performed on the frozen soils:

- removing the floor for base freezing by natural cold air,
- excavation of the ground surface under the floor to create an air space 0.5 m deep,
- arrangement of air-holes measuring 0.4 × 0.2 m in the walls of the foundations.

The deformations stopped during the years following the renovations. However, it was necessary to strengthen the walls in the 1980’s because the bearing walls of the building had numerous cracks in them and so the design was developed in 1997–1998. The building has been under operation once more since 1987.

The Preobrazhen Church was built in 1845. At the beginning of the restoration, the original plan and design of the building were unavailable (Fig. 1).
Nothing was known about the previous reinforcement works. Favourable permafrost-soil conditions probably caused an opportunity for building preservation without any additional measures being required to keep the soil in a frozen state. The main cross walls and the arches had cracks due to insufficient connections at the overlap and low stability of the high brick walls.

The Real School is a two-storey building, II-shaped in plan, and was constructed in 1911 according to the design of the architect N.B. Baumgarten, again without measures to preserve the permafrost. In one year, the operation of the building was stopped due to excessive deformations and it took 18 years to refreeze the base. In 1940, the floor was again disassembled due to new deformations, and air-ventilated space was made for cold air to be circulated through the air-holes in the foundations. Over the last 20 years, the settlements have accelerated again. In 2000, a design for strengthening and reconstruction of the National Museum building was developed.

The following sections describe the soil conditions and foundations as well as the modes of strengthening the foundations.

3 FROZEN SOIL CONDITIONS AND FOUNDATIONS

All of the buildings discussed herein were constructed on strip foundations; a method that is widely used in a temperate climatic zone. The measures carried out previously were directed at stabilization of deformations and involved freezing the thawed ground by the provision of an air void. However, despite strengthening of the bases, the buildings continued to deform after a period of time.

To reach appropriate design decisions about strengthening the bases and foundations, an analysis of the soil conditions resulting from thawing and subsequent refreeze at the bases of the buildings has been carried out. The strip foundations were inspected by excavating trial pits adjacent to them. Soil properties were studied and the durability of rubble-work stones and the weak lime based sand mortar was evaluated.

The soils lying beneath the National Library within the active layer are represented by clayey soil with some occurrence of particle grading sizes from silty to medium sand. Compared to the soils at the site, which lie outside the construction activity, they feature high ice content and a layered cryogenic texture. This testifies that the formation of ice-rich soils at the base is associated with the development of a zone of thaw before installation of air-holes and subsequent freezing. The maximum values of moisture content, 95–101%, are representative of soils occurring from just below the foundation base down to 5 m. Ice-veins, ice-jacking and ice as a crust were found in the lower part and in the top layers of the damaged foundation.

The ice content in the foundation wall was confined to weathered sandstones and layers of a lime-based mortar. Soils are characterised by low temperatures, from −4.3 to −5.9°C at a depth of 10 m. Study of the deformation properties of icy soils showed high compressibility at calculated temperatures from −0.9 up to −5.5°C. According to compressive tests on plastic-frozen ice-rich sand of undisturbed structure, sampled at the base of the given object, the deformation modulus at a temperature of −1°C was lower than 5 MPa, increasing only up to 15 MPa at a temperature of −5°C. The values of the deformation moduli for sand, with massive cryogenic texture at the moisture content less than complete moisture capacity at the same temperatures, are 15–33 MPa. These data lead to the conclusion that non-uniform occurrence and distribution of ice-rich soil immediately below the foundation base caused the regeneration of building deformation after base refreezing (YDRIC 1997).

The occurrence of ice rich soils below the foundation base was also established at the Real School, where a thaw area also formed during the first years of operation. The progressive non-uniform foundation settlements were established by survey, with preservation of fairly low soil temperatures (from −3.3 to −5.1°C at a depth of 10 m). At this site the total moisture content of soils just below the foundation base was 33–84%. Maximum settlements were found under part of the building, where ice-rich loam occurred below the base. For this corner of the building, frost heaving was also observed during the winter. The foundation inspection pit showed that the rubble-work stones were strongly weathered, dolomites at the bottom were broken with horizontal cracks up to 1.5–2 cm thick, the infill was loose, and there were ice-filled voids in the foundation.

Soil conditions at the base of Preobrazhen Church differ considerably from those above. The Church was built on a hill, with more favourable soil conditions. The soils below the base of foundation were mainly fine and medium sand, with massive cryogenic texture. The moisture content is 23–29% and the soil is near saturation. Loam and sandy loam together with building rubble filled the centre of the foundations. This, in turn, served as a waterproofing layer that probably preserved the natural moisture content characteristics of the soils within the thaw depth. Permafrost exists at relatively low temperatures in Yakutsk: from −4.6 to −6.1°C. The normal depth of the active layer is between 2.6 and 3.0 m and strip foundations are founded at a depth of 1.9–2.35 m from the surface. Inspection of foundations revealed that the top part of the foundations had a flange below a bearing wall transmitting the loads from the bell tower. Rubble stones in the foundations, up to 0.8 m depth, appeared to be strongly weathered,
4 DESIGN DECISIONS ON FOUNDATION STRENGTHENING

To take a decision on foundation strengthening, the following factors were taken into account:

– weathering of the strip foundations especially within the active layer,
– high compressibility of the soils below the foundation base,
– the depth of the foundation compared to the depth of active layer.

Creep of ice rich soils occurring directly beneath the foundation base of National Library and Real School necessitated the following actions:

– strengthening of the existing strip foundations within the maximum thaw depth by cementation to eliminate defects, i.e. weathered zones, voids, destructions of the rubble-work and replacement of weak lime-sandy cement,
– installation of injection piles (micropiles) below the strip foundations for transmitting the load to the deep hard frozen medium to fine sand,
– restoration of existing and installation of new air-holes, ensuring preservation of the permafrost regime at the base of the footing.

The strip foundations of Preobrazhen Church rest on fine to medium sand, which are hard frozen and are practically incompressible. The installation of micropiles was not necessary. An increase in the load and presence of cracks on internal walls required foundation strengthening below these internal walls through a reinforced concrete casing supplied to enhance the width of the foundations. This was required by the fact that the foundation base rested on the permafrost table, i.e. in the fall the temperature of the soil is close to 0°C. The floor was made of beams set on separate posts. Thermal insulation is stipulated around the outside perimeter of the building, 1.2 m wide.

Cementation of strip foundations and micropile installation were new designs for permafrost areas. These technologies are widely used in thawed soils for reconstruction and strengthening of existing buildings.

Cementation of shallow foundations on permafrost is limited by the terms of performance for these works. The main design requirement was a necessity for the work to be performed during the autumn period, i.e. during maximum thaw of the foundation. Cementation was carried out in September – October, and partially into November in 1998. The most challenging technological task in association with installation of micropiles was hardening of the concrete.

Previously, laboratory tests were carried out to determine the hardening kinetics of various slurries at low temperature. Plastic and chemical additives were mixed to form a compound that guaranteed cement hardening at temperatures from –4 up to as low as –10°C. Thus, the strength of the slurry reached 20 MPa in 28 days.

Micropiles were installed for underpinning the foundations of the National Library by the Czech firm “Svratka”. The micropiles were 140 mm in diameter and were placed inclined from both sides of foundations. The pile lengths were up to 8 m spaced at 1–1.2 m centres, and were embedded in the underlying hard frozen dense sand, which had a massive cryogenic texture. In total, 228 piles were installed.

To estimate the reliability of the design decision to reinforce the foundation with micropiles, static tests have been carried out on the piles under increasing load steps. The tests were conducted according to the requirements of GOST 5686-94 for the technique of controlling tests during construction. The experimental piles, 6 and 5 m long, were installed in the most adverse soil conditions. Constant control of the soil temperature and slurry hardening has been carried out during pile installation and tests. Based on test results, the limiting resistance of the piles was found to be 500 kN for 6 m long piles and 350 kN for piles of 5 m length. In view of this data the bearing capacity of the
8 m long micropiles was recalculated for the most unfavourable conditions to be 300 kN for each pile.

5 CONCLUSION

The application of construction procedures common in temperate zones to construction under permafrost conditions allowed for restoration of the Preobrazhen Church (Fig. 2). The restoration work is still underway for the other structures. The strengthening of the foundation bases requires micropiles and cementation for the National Library and cementation for the Real School of the National Art Museum. The observations conducted at the National Library building showed that the cracking of the building has now stopped.

REFERENCES


GOST 5686-94 Soils. Field test methods by piles 43. Moscow: Gosstandart.