Numerical analysis and practical application of methods for strengthening foundations with piles during reconstruction process

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Abstract. The article describes the reconstruction of the historical stone building basements. It provides a brief description of the constructive solution of the buildings under consideration and summarizes information about their technical condition. The article highlights the importance of analyzing information about the construction and operation of buildings during the entire history. This article lists the main tasks of the reconstruction of historical buildings: area augmentation due to the reconstruction of previously unexploited basements, deepening of basements, expansion of existing openings in the walls and construction of new ones, arrangement of new entrance nodes into the basements of a building, etc. Besides, the article gives a brief description of the soil conditions of the reconstructed buildings sites, which are typical for historical buildings in Tomsk. It points out the need for thorough engineering and geological examinations with additional geotechnical examination of the soil base. Additionally, the paper clarifies the necessity to examine the characteristics of supporting layer foundation soils, changed due to their compaction by the weight of the building during the period of long-term operation. The results obtained during the examination and assessment of the technical condition of foundations and overhead building structures will be presented. Also, this study proposes classification of methods for strengthening natural foundations (free-standing, strip, slab and massive) using piles. In particular, it talks about piles that are installed without soil extraction - displacement piles (pressed and injected), as well as examples of numerical modeling of the work of detached and strip foundations reinforced with the use of piles when the basement floor elevations are lowered. Finally, it shows experience of scientific and technical support for the reconstruction of buildings.

1. Introduction

Most of the historical stone buildings in Tomsk were erected between 1850-1900. These buildings are cultural heritage monuments. During the period of their long-term maintenance (over 100 years), a significant number of defects and damages have accumulated in the building structures. The physical deterioration of such buildings reaches 60% or more, therefore reconstruction and restoration are required. When solving issues of reconstruction (restoration) of historical buildings, one of the main tasks is to restore (strengthen) building structures, taking into account the conversion of previously unexploited basements into operated premises while deepening them. Deepening of basements and strengthening of aboveground structures leads to an increased strain on the foundation [1, 2].
addition, during the period of long-term operation of buildings, the physical and mechanical characteristics of the base soils inevitably deteriorate due to their prolonged soaking with melt and technogenic waters. [1-3]. All this inevitably leads to the need to strengthen the foundations. One of the most rational ways for strengthening natural foundations on weak clayey soils is to strengthen them using piles (injected, pressed). The stone historical buildings of Tomsk are two-three-storey (figure 1), often complex in shape (figure 2(a)). The buildings have a compound structural design with longitudinal and transverse walls and internal brick pillars. The structural design of buildings was changed to an internal incomplete reinforced concrete frame during its maintenance, particularly during the reconstruction in 1970-1985. Foundations of buildings under external, internal walls and internal pillars are often tape and free-standing, rubble on lime-sand mortar. The walls of the buildings are made of red ceramic bricks with lime and lime-sand mortar. The basement walls are usually rubble with lime-sand mortar and brick made of red ceramic bricks. Ceilings are brick vaults on steel beams. During the reconstruction of 1970-1985, the floors in many buildings were completely replaced to reinforced concrete, monolithic on metal and reinforced concrete beams. The roof of the buildings is rafter, pitched.

![Figure 1](image1.png)  
**Figure 1.** General view of historical stone buildings in Tomsk.

### 2. Experimental technique and theoretical approaches

The examination of foundations was usually carried out from pits, which were laid in the most characteristic places of the building plan. These pits were simultaneously used to examine the basement soils. The number and size of the pits were determined by the dimensions of the building and its design features, the soil conditions of the construction site, the condition of the foundations and other above-ground building structures. In buildings with a basement, the pits were usually laid inside the basement, which made it possible to reduce the amount of earthwork.

When examining foundations in open pits, the type of foundations, their shape in plan, dimensions, and depth were specified. At the same time, the strength of the foundation material was determined and masonry defects (for strip, stone and concrete foundations), the presence of cracks, as well as previously performed connections and reinforcements were identified. The strength of the foundation material was determined by destructive and non-destructive methods, depending on the tasks set during the examination, as well as the instruments and equipment available.

During the examination of long-term exploited buildings, special attention was paid to waterproofing basement walls and foundations, as well as the mode of changing the level of groundwater. In big cities, an increase in the level of groundwater is often noted, due to water leaks from external sewerage networks, water supply systems, heating mains, violations of engineering preparation of territories and other reasons. Therefore, when examining the foundations and soils of the base, sources of soaking were established in order to subsequently provide technical solutions for their elimination. Based on the results of the foundations examination (including the soils of the base)
and identified defects, an assessment of their technical condition (visual, instrumental) was given. During the assessment, the nature and direction of the development of cracks, the boundaries of areas of local destruction or rupture of foundations, the place where the bases were soaked were determined, and the category of their technical condition was established (according to the current regulatory documents). When assessing the technical condition of foundations (including basement soils) and other above-ground building structures, the question of the causes of defects or damages has always been extremely important.

During the reconstruction and restoration of buildings, the following tasks are usually set: increasing the existing areas of the basement; increasing the height of the basement rooms; expansion of existing and installation of new doorways in the internal load-bearing walls of the building's basement; the device of new entrance nodes to the basement of the building [1-4, 5, 6]. Taking into account the tasks of reconstruction, the structural scheme of the building is sometimes changed. For example, when constructing wide openings (figure 2 (a) and 2(b)) in the inner walls, according to the conditions for transferring loads to the base, the foundations are rebuilt from tape to stand-alone ones. With an increase in the height of the basement rooms, the soles of the existing foundations became higher than the basement floor mark. All this, together with the technical condition of the building structures, resulted in the need to strengthen the foundations.

![Figure 2](image.png)

**Figure 2.** Basement plan of the administrative and commercial building on Lenin Avenue: (a) - before the reconstruction; (b) - after the reconstruction.

Mentioned above reconstruction and restoration tasks were carried out by the employees of Kuban State Architectural University, Tomsk State Architectural and Building University [6, 15, 14] with the participation of SNPO Geotom Ltd, and NPO Georekonstruktisiya Company from 2001 to 2013. Scientific and technical support for the reconstruction of the basements of buildings included: collection and analysis of archives for the building, assessment of the ground conditions of the site with examination of the soils and the bearing layer of foundations, hydrogeological observations of the groundwater existence in the basement of the building with the establishment of sources of soaking, examination and assessment of aboveground building structures technical condition, verification calculations via Midas GTS NX PC and Plaxis PC programmes, development of technical solutions for the restoration (reinforcement) of building structures, geotechnical monitoring (observation) of foundations deformations, and the state of building structures.
3. Results

3.1. Base soils study
The sites of buildings under reconstruction in Tomsk, according to SP 47, 13330.2019, usually fall under the II-III category of engineering and geological conditions complexity. Upper Quaternary (aQ1V) deposits of the high floodplain of the Tom River at the contact with deposits of the slope of the Tom-Yai watershed, overlapped from the surface by modern technogenic deposits (QV1), take part in the geological and lithological structure of the sites within the explored depth of 12.0-15.0 m. Typical engineering-geological sections of the sites (figure 3) from the surface are represented by: filled soil with sandy loam, or loam with the inclusion of slag, gravel, broken brick, peat; loams from fluid to soft-plastic with an admixture of organic matter up to 9%; fluid sandy loam, widespread in the thickness of loam in the form of lenses and interlayers; fine water-saturated sand, distributed in the form of an interlayer in the base of a loamy strata; pebble soil with sandy aggregate, watered. At the sites a complex of underground waters is usually exposed, consisting of 2 - 3 layers of underground waters. The technogenic aquifer of the "top water" type usually spreads in the bulk of the fill soils at a depth of 2.2-5 m near the base of the foundations; an aquifer of the high floodplain of the Tom River, free-flowing in nature, is found in flowing sandy loams at a depth of 4.4 - 5.3 m. The water confinement is an interlayer of soft-plastic loam, lying at a depth of 8.6 - 10.3 m. The third underground water layer of alluvial deposits of the floodplain of the Tom River, confined to flowing sandy loams, fine sand and gravel deposits, occurs at a depth of 9.2 - 10.6 m.

![Figure 3. Typical engineering-geological sections of the reconstructed buildings sites.](image)

Taking into account the complex hydrogeological conditions of the sites of the buildings in use, observations are usually organized to look out for the appearance of groundwater at the base of the foundations [13]. In the basements along the perimeter of the building, observation wells were installed to a depth of 3.5-4.0 m below the existing basement floor. The results of chemical analysis of ground waters indicate that soaking of the foundation basements occurs due to the seasonal rise in the groundwater level (upper water) during the period of snow melting and heavy rains. In addition, the formation of the groundwater level at the base of the foundations is influenced by the leakage of domestic wastes from the internal and external sewerages.

3.2. The results of the base and foundations examination
During the examination of basement foundations, the presence of defects and damage was established [6, 15, 16]. Most of the defects and damages were detected at the foundations under the outer walls and areas under the inner walls adjacent to the outer walls. Simultaneously, stratification of rubble masonry of foundations, dumping of rubble masonry stones, subsidence of foundations was observed. In addition, the lime-sand mortar in the rubble masonry foundations crumbled due to its long-term
intensive soaking. Typical results of assessing the loading of the foundation base show that the pressure (p) along the bottom of the foundations is in most cases less than the design resistance of the foundation soil (R) at p / R = 0.64-0.95 (64-95%). However, areas with the most loaded foundations were inevitably identified, where, taking into account the changed characteristics of the soils when the base was soaked, the pressure (p) along the sole exceeded the design resistance (R) from 1% to 50%. The results of verification calculations of the base of foundations for deformations usually show that the absolute values of the final settlement and relative deformations of the foundations base (ΔS / L) in most cases exceed the maximum permissible values. However, these calculated deformations have already happened during the long-term operation of the building, and the base is mainly in a stabilized state. The results of the bearing capacity calculations usually ensure the stability of the foundation of the building foundations.

As a result of the basement and foundations examination it was determined, that there was the need for a whole range of repair and restoration work. At the same time, it was decided to strengthen the foundations, walls, floors and other building structures of buildings. The analysis of the accumulated experience of reconstruction and restoration of buildings made it possible to generalize the existing methods of strengthening shallow foundations using additional piling of various structures. Also, displacement piles are considered, during the construction of which soil extraction (well drilling) is not performed - these are mainly indentation piles and injection piles. For natural foundations, free-standing, strip, slab and massive bases are considered. The location of the piles is considered either under the base of the existing foundations, or in the form of outrigger (adjoining) piles.

3.3. Numerical modeling of options for strengthening foundations with piles

The assessment of the stress-strain state of soils at the base of the foundations for buildings under reconstruction is carried out in a three-dimensional formulation in the Midas GTS NX PC, sometimes in the Plaxis PC programme. At the first stage, computational models are developed, which, if necessary, are adjusted along the process. For modeling the work of foundations, piles, walls and other building structures the Elastic models are used; for soils - Mohr-Coulomb and Hardening Soil (HS). During the modeling, a three-dimensional model of the existing foundations of the entire building is firstly created. The analysis of the stress-strain state of the foundation is carried out under the actual design solution and the existing loads before reconstruction. Comparison of the settlement of foundations in different parts of the building, obtained during modeling, makes it possible to assess the reliability of the calculated results.

![Diagram](image)

**Figure 4.** Design diagrams of a detached foundation in the Midas GTS NX PC: (a) – before strengthening; (b) – when installing piles under the base of the foundation; (c) – when installing external (adjoining) piles.
At the second stage of modeling, the stress-strain state of the base of each of the types of foundations available in the building is assessed separately (figure 4). Areas are considered where the constructive solution of foundations and engineering-geological conditions change, the results of geotechnical examination are taken into account. At this stage, the choice of a method for strengthening the foundations is made. Various options for strengthening foundations using piles (under the base, remote and others) are considered and tested via modelling. This changes the diameter and length of the piles, their number and planned location (figure 4). A block diagram of the classification of methods for strengthening shallow foundations using piles is shown in figure 5. The main criteria when choosing a strengthening method is to limit the additional settlement of foundations (usually 10-20 mm), as well as its manufacturability and labor intensity.

**Figure 5.** Classification of methods for strengthening shallow foundations using piles (subspecies of each of the strengthening methods are not presented).

In the conditions of reconstruction and restoration of buildings, to simulate the work of piles near the foot of the foundations, the characteristics of soils are usually used, for which the regularities of their change during compaction have been previously identified [1-4, 13, 14, 15]. An important issue when modeling additionally arranged piles is taking into account the change in the stress-strain state of the base under the bottom of the foundation due to their construction. This is especially true for displacement piles (pressed, injection, and others). One of the widespread methods of accounting for changes in soil properties around piles during modeling is a change in their characteristics in the near-pile array (usually in a 3d radius). Those are the characteristics of density, specific cohesion, modulus of soil deformation, etc., which differ from characteristics for soils of natural constitution [1-4]. However, this approach is not sufficient for modeling displacement piles (pressed and injection). Therefore, it is necessary to take into account not only the change in the stress-strain state at the base from the pressure of the building, but also the technology of piling, for example, by displacing the soil to the sides by expanding a cylindrical well from an almost zero diameter (1-10 mm) to a pile diameter...
(250-300 mm). It is also possible to foresee the movement of the pile tip downward from 0.5 to 1.0 m. Such calculation can be done using the Prescribed displacement tool - prescribed displacements (for pressed piles), or axisymmetric expansion of the well with internal pressure (for injection piles).

When modeling options for strengthening foundations (including the lowering of the basement floor elevations), step-by-step calculations are made, taking into account all technological operations of the work using the Construction stage function (which is also called a phased construction). After modeling the initial state (before reconstruction), needed calculations are made for replacing (or installing brand new) elements of foundations, installing piles, excavating soil, etc. To determine the necessary stages of the calculation, the entire technological scheme for strengthening the foundations is being worked out, for which geometric and design schemes are drawn up.

The third stage of modeling was performed after analyzing the simulation results, selecting and adjusting the amplification schemes for individual sections of strip and free-standing foundations. Additionally, a design scheme for strengthening the foundations for the entire building was formed. This approach allows to take into account the mutual influence of the adopted schemes for strengthening foundations in adjacent areas. After the performed analysis of the simulation results, the adopted scheme of strengthening the foundations in individual sections can be adjusted, if necessary.

4. Conclusion
As a result of the described examinations it has been established that the numerical modeling for the operation of reconstructed buildings foundations must be considered together with the history of their loading, detailed data on the technical condition and data from the foundation soils examination.

When modeling the operation of injection piles, arranged to strengthen the foundations of reconstructed buildings, it is necessary to take into account the technology of their construction. For such type of piles, it is not enough to designate a fixed compacted zone of the massif around the shaft in the design scheme. Instead, it is necessary to simulate the expansion of the well when the concrete mixture is injected through the injector. Modeling the operation of the reconstructed building foundation is recommended to be carried out in stages: first, the foundation is explored and the reliability of the adopted soil models and calculation schemes is considered. Then technological schemes and modeling options are developed. Next, a choice of options for strengthening the foundations is made, as well as modeling the joint work of reinforced foundations for the entire building.

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