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BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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TECHNOLOGY FOR RESTORING THE DEFORMED STATE OF PRISMATIC AND OTHER TYPES OF BUILDINGS THROUGH FOUNDATION BASE STIFFNESS CONTROL

Purpose. The article is aimed at presenting effective technologies and engineering methods developed for restoring the deformed state of buildings and structures that have undergone uneven foundation settlements, with a particular focus on eliminating tilts and ensuring further safe and reliable operation of such objects. **Methodology.** The proposed restoration approach is based on controlling the stiffness of foundation soils by means of drilling horizontal boreholes with variable geometric parameters beneath the less-settled portion of the structure. Partial soil removal causes a regulated reduction of base stiffness, enabling the structural system to gradually return to its design position. The stiffness adjustment is justified through the deformational characteristics of the soil and expressed by the ratio between average foundation pressure and corresponding settlement. In cases of complex tilt behavior, additional stabilization is ensured through horizontal soil reinforcement using soil-mixing technology to form rigid soil-cement elements. The implementation of the method is supported by specialized technological equipment, including multi-speed horizontal and vertical drilling systems designed to operate under varying soil conditions. **Findings.** The method demonstrates efficiency in eliminating tilts of buildings of prismatic configuration in transverse, longitudinal, and combined directions. It also proves effective for removing related deformation forms such as sagging, bending, distortion, and torsional displacement. More than 70 buildings and structures of different types were successfully restored in various regions of Ukraine without interrupting functional activity or relocating residents. **Originality.** The restoration effect is achieved not by applying forces directly to the building structures, but by controlled modification of the soil base stiffness, which significantly reduces structural risks and eliminates the need for heavy jacking or structural detachment. **Practical value.** The proposed technologies ensure safe, economically feasible restoration of buildings, extending their service life and guaranteeing stable operation under real urban and geological constraints.

Keywords: deformations; restoration of the deformed state; foundation base stiffness; horizontal boreholes; regulation of foundation settlements

Introduction

Construction and operation of buildings and structures on territories composed of weak and structurally unstable soils, as well as in mining regions, is complicated by the fact that, as a result of negative technogenic impacts on foundation bases, a large number of damaged building structures arise. Most often, the damage to buildings and structures occurs due to uneven deformations of the soil bases and, consequently, uneven settlement of foundations. In this case, different types of deformations of buildings and structures occur- bending, sagging, relative displacement of structural elements, and others – but the most complex deformations are tilts.

Particularly severe consequences of deformations are inclinations of buildings and structures, when they or their parts (block-sections) are locked together in various configurations through deformation joints. The tendency of inclined buildings is that the tilt increases due to the appearance of eccentricity of the center of gravity and redistribution of pressure from the foundations to the soil with its increase toward the side of the tilt. In the case of opposing tilts, the width of the deformation joints decreases. The increase of opposing tilts over time leads to the closure of gaps between adjacent buildings (deformation joints) and, consequently, to the appearance of mutual pressures. Mutual pressure increases over time, leading to deformation of structural elements and the development of an emergency state of buildings (Fig. 1).

Fig. 1. Emergency building No. 6
on Voronezka Street in Zaporizhzhia

Tilts are dangerous not only in cases of mutual inclination of adjacent buildings but also in cases of individual structures. When eccentricity of a building's center of gravity occurs, bending moments arise, leading to significant deformations of various types, which increase over time until emergency situations develop. Therefore, to prevent such occurrences, it is necessary to eliminate building and structure tilts in a timely manner.

The second problem associated with restoring deformed buildings is as follows. Research and inspection practices of damaged buildings show that the main causes of damage are uneven deformations of soil bases due to technogenic impacts on soils, which cause uneven foundation settlements. Therefore, when restoring deformed buildings, in order to ensure their further reliable operation, it is often necessary to strengthen the bases (Петренко, Крисан, В. І., Крисан, В. В., & Коновал, 2022; Раздуй, & Винников, 2023; Yao, K., Yao, Z., Song, et al., 2016). Strengthening of the bases should be carried out immediately after eliminating the deformed state of the buildings.

A sufficient number of studies are devoted to the issue of deformations of building structures, in which the causes of deformation and methods of their elimination are described (Шокарев, 2008).

There are various types of building deformations: sagging, bending, tilting, etc. Most of them result from uneven settlement of foundations during operation due to uneven soil deformations caused by deterioration of soil properties for various reasons. In scientific sources, it is noted that one of the most dangerous types of deformations is tilt, because it occurs in different directions, which may lead to opposing inclinations of buildings, structures, and their parts. When opposing tilts come into contact, mutual pressures arise, which, if the contacting buildings are not separated promptly, lead to significant consequences up to destruction. An example of such a situation is shown in Fig. 1.

Taking into account the complexity of this type of deformation, we will demonstrate the essence of this article using its example. There are various technologies for eliminating tilts. One of the most researched and commonly used methods is the elimination of inclinations and separation of contacting structures using jacking systems (Трегуб, Москаліна, Науменко, & Мілявський, 2008). This method is also applied in the elimination of tilts of engineering structures. However, the use of jacking systems for restoring deformed structures has significant disadvantages: first, the influence of high concentrated forces on building structures, which causes several difficulties, for example, the need to strengthen the foundation-wall section; the need to detach the foundation part of the building from the above-foundation structure by cutting them apart; and other inconveniences (Болотов, Зотов, В. Д. & Зотов, М. В., 2004).

The object of influence during restoration of the deformed state using jacking systems is the building structure itself. More safe and effective are restoration methods based on technologies that affect the foundation bases directly.

Purpose

The purpose of this article is to present the effective technologies and methods we have developed for restoring deformed buildings, which ensure their further reliable operation.

Methodology

At the level of invention (Patent of Ukraine No. 65455A) (Степура, Шокарев, Павлов, & Трегуб, 2003), we developed a method for eliminating the deformed state of buildings, in particular the elimination of tilts, by partially removing excess soil that prevents the building foundation from returning to its horizontal position. This is achieved by drilling horizontal boreholes of variable parameters in the soil base beneath the less-settled part of the

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foundation, i.e., on the side opposite to the direction of the tilt. Partial removal of soil from beneath the foundation is equivalent to changing the stiffness of the soil base (Alsirawan, Koch, & Alnmr, 2023; Fischer, 2022).

The stiffness of the soil base is a deformation characteristic that indicates the ability of the base to resist applied loads and is characterized by the stiffness coefficient. The stiffness coefficient of any area of the foundation base surface represents the force that must be applied to a unit area in order to displace it by a unit distance. Under vertical load acting from the building, the stiffness coefficient is determined by the formula:

$$K = P/S, \quad (1)$$

where: P – the average pressure under the foundation base, and S – is the settlement of the foundation under pressure P.

Since the drilling of horizontal boreholes is a controlled process in accordance with the calculated borehole parameters, this method is essentially reduced to regulating the change in the stiffness of the soil base.

Findings

The innovative method developed for restoring the deformed state of building structures by controlling the stiffness of the foundation bases is well adapted for eliminating deformations in buildings of prismatic shape. However, in its application, certain situations arise that must be taken into account, and special technologies should be applied to regulate these conditions. The explanation of this statement will be demonstrated using the example of eliminating tilts in prismatic buildings.

Buildings of prismatic shape may tilt in transverse, longitudinal, and complex directions, that is, simultaneously in two directions close to a diagonal. Figures 2-3 show examples of tilts in the transverse direction (Fig. 2) and in the longitudinal direction (Fig. 3). According to the developed method, the restoration of such buildings to their design position is carried out by drilling horizontal boreholes. To eliminate a transverse tilt along the length of the building, horizontal boreholes of variable parameters (i.e., stepped boreholes) are drilled under the foundation in the transverse direction. To eliminate a longitudinal tilt, horizontal boreholes (also stepped) may likewise be drilled under the foundation, in this case along the length of the building (block-section). However, such a drilling scheme is significantly more complex due to the possible length of the building, and may not always be feasible – for example, due to the adjacency of neighboring buildings or block-sections. Therefore, drilling is carried out across the building with varying borehole parameters (diameters, spacing) along the drilling front.

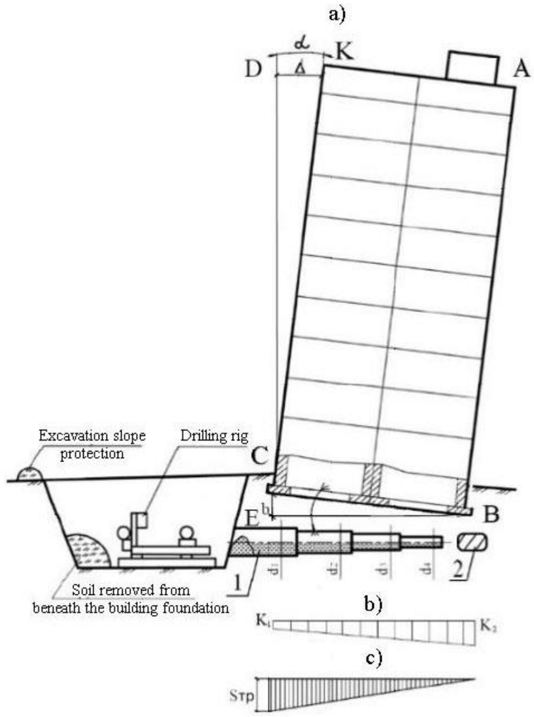

Fig. 2. Technological scheme of building leveling in the transverse direction:
a) parameters of the transverse tilt and variable-cross-section borehole
b) change in the required stiffness of the foundation base;
c) diagram of the required technological settlements of the foundations;
1 – horizontal borehole;
2 – horizontal soil reinforcement

It must be taken into account that, when eliminating tilts in this way, the facades A-B will undergo active lowering. However, due to the plastic deformation of the soil, the facades C-D may also begin to move, which must be prevented. In this case, stabilization of the C-D facades is recommended to be performed by strengthening the soil beneath them through the installation of rigid horizontal soil-cement elements (item 2, Fig. 2, 3) using the horizontal reinforcement method based on the soil-mixing technology, according to the technological scheme shown in Fig. 4 (Юхименко, 2014).

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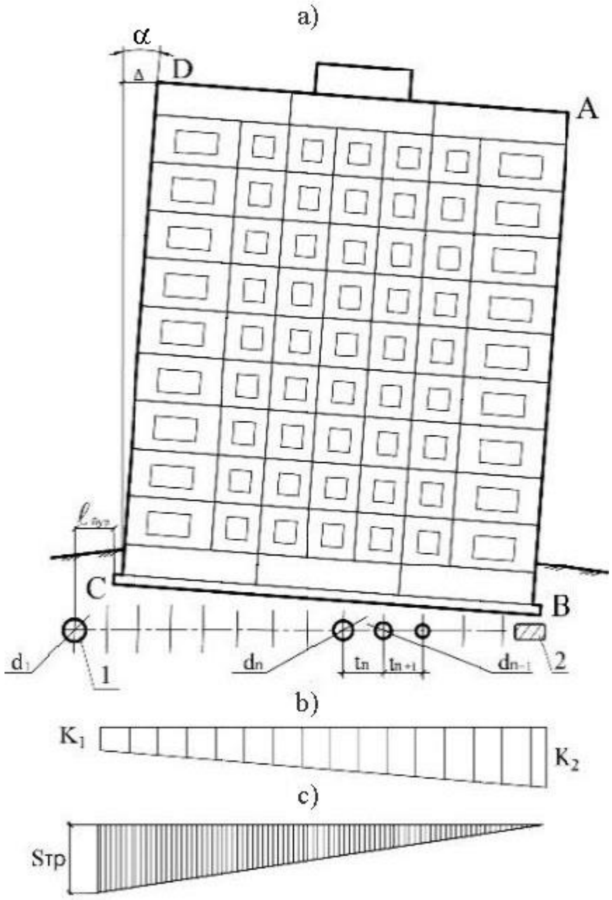

Fig. 3. Technological scheme for eliminating the longitudinal tilt of the building:
a) parameters of the longitudinal tilt and the borehole layout scheme;
b) change in the required stiffness of the foundation base;
c) diagram of the required technological settlements of the foundation;
1 – horizontal boreholes; 2 – horizontal soil reinforcement

a) b)

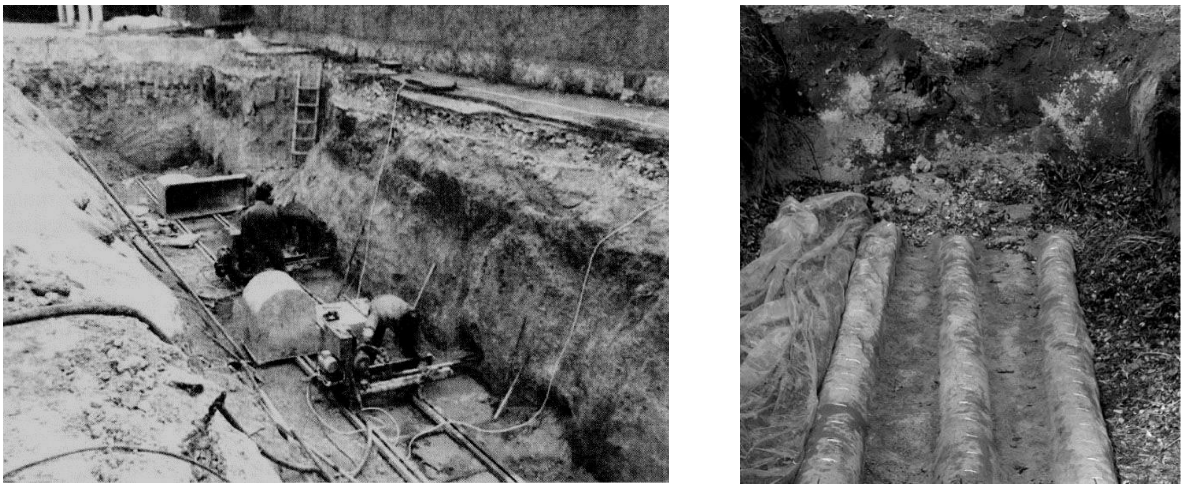

Fig. 4. Technological scheme of horizontal soil reinforcement of the foundation base:
a) fragment of the horizontal reinforcement technology; b) exposed horizontal soil-cement elements

In work (Шокарев, Степура, Самченко, & Павлов, 2012), an example is provided of restoring the deformed state of a ten-story building by leveling through horizontal borehole drilling and strengthening of the foundation base using horizontal soil reinforcement by soil-mixing technology.

To implement the developed restoration technologies, under the scientific and technical leadership of Ph.D. Samchenko R. V., technological equipment was designed and manufactured based on the related inventions, including horizontal drilling machines for boreholes (Юхименко, Павлов, Самченко, & Степура, 2013) and machines for horizontal soil strengthening after the elimination of the deformed state, when necessary, as determined by the methodology also developed by him. Additionally, vertical drilling machines (Patent of Ukraine) (Самченко, Степура, Шокарев, & Юхименко, 2012) were developed for constructing retaining walls of foundations and protecting the walls of pits or trenches from which horizontal borehole drilling and soil strengthening of the foundation bases are carried out in constrained restoration conditions.

During the investigation of the operation of these drilling machines in the course of restoration technologies, certain shortcomings were identified, the main of which was the use of single-speed axial and rotational movements. This is significant when applying these technologies under conditions of varying soil properties. Therefore, the machines were improved and now provide three-speed modes for both axial and rotational motion, which are discussed in detail in the dissertation research of Ph.D. Yukhymenko A. I. This has made it possible to determine rational operating modes during restoration technological processes under conditions of changing soil properties.

Originality and practical value

The presented technologies make it possible not only to eliminate tilts of structures, but also to remove deformation forms such as sags, bends, separation of contacting buildings, as well as to eliminate distortions and torsional deformations of buildings.

Using these technologies, more than 70 buildings and structures of various purposes have been restored in different regions of Ukraine and under different soil conditions. At the same time, the restoration of the deformed state was carried out without relocation of residents, without interruption of industrial or functional activity, and without increasing the deformation of the structures.

Conclusions

A unified method has been developed for restoring the deformed state of buildings and structures by controlling the stiffness of the foundation bases, which makes it possible to regulate foundation settlements; this universal method ensures the restoration of various structural systems under different types of deformations, as confirmed by the successful restoration of more than 70 buildings and structures, while the applied technologies ensure their normal further operation and consequently extend their service life.

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ТЕХНОЛОГІЯ ВІДНОВЛЕННЯ ДЕФОРМОВАНОГО СТАНУ БУДІВЕЛЬ ПРИЗМАТИЧНОЇ ТА ІНШИХ ФОРМ УПРАВЛІННЯ ЖОРСТКОСТІ ОСНОВ

Мета. Стаття спрямована на представлення ефективних технологій та інженерних методів, розроблених для відновлення деформованого стану будівель і споруд, що зазнали нерівномірних осідань фундаментів, з особливим акцентом на усунення кренів та забезпечення подальшої безпечної і надійної експлуатації таких об’єктів. **Методика.** Запропонований підхід до відновлення ґрунтується на керуванні жорсткістю ґрунтів основ шляхом буріння горизонтальних свердловин зі змінними геометричними параметрами під менш осілою частиною споруди. Часткове видалення ґрунту викликає регульоване зменшення жорсткості основи, що дозволяє конструкції поступово повернутися до проєктного положення. Регулювання жорсткості обґрунтовується деформаційними характеристиками ґрунту та виражається відношенням середнього тиску під підошвою фундаменту до відповідного осідання. У випадках складної форми крену додаткова стабілізація забезпечується горизонтальним армуванням ґрунтів за технологією ґрунтоцементації з формуванням жорстких ґрунтоцементних елементів. Реалізація методу здійснюється за допомогою спеціалізованого технологічного обладнання, зокрема багатошвидкісних горизонтальних і вертикальних бурових установок, адаптованих до роботи в умовах змінних властивостей ґрунтів. **Результати.** Метод продемонстрував ефективність в усуненні кренів будівель призматичної форми в поперечному, поздовжньому та комбінованому напрямках. Він також показав результативність при усуненні супутніх деформацій, таких як прогини, вигини, перекоси та крутіння. Понад 70 будівель і споруд різного призначення було успішно відновлено в різних регіонах України без припинення їхньої функціональної діяльності та без відселення мешканців. **Наукова новизна.** Ефект відновлення досягається не шляхом прикладення сил безпосередньо до конструкцій будівлі, а через керовану зміну жорсткості ґрунтової основи, що суттєво зменшує конструктивні ризики та усуває потребу у застосуванні домкратних систем або розрізанні конструктивних елементів. **Практична значимість.** Запропоновані технології забезпечують безпечне та економічно доцільне відновлення будівель, подовжують термін їх експлуатації та гарантують стабільну роботу в умовах реальних міських і геологічних обмежень.

Ключові слова: деформації; відновлення деформованого стану; жорсткість основ; горизонтальні свердловини; регулювання осідань фундаментів

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