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APPLICATION OF NANOMATERIALS AND NANOTECHNOLOGIES IN CONSTRUCTION

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Development of performance requirements for grouting mixtures in soil improvement by pressure injection

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ABSTRACT

Introduction. The geotechnical environment is a dynamic system, the parameters of which are pivotal in determining the reliability and safety of building and structural engineering works. Deterioration in soil properties, whether of a natural or human-induced origin, gives rise to conditions that deviate from the design specifications, thus necessitating the implementation of protective measures in the form of soil stabilization. The process entails the reinforcement of soil, resulting in the formation of a three-dimensional geotechnical massif. In this context, the microstructure of the treated soil is partially or completely filled with an grouting mixture. This enhancement leads to improvements in both cohesion and de-formation characteristics, relative to the initial values. Injection methods have been employed extensively to address a wide range of geotechnical challenges, with the objective of stabilizing and enhancing soil properties using polymeric or mineral compositions. However, the requirements for such compositions are often either not specified or stated only in general terms, and many methodologies and the underlying assumptions for design justifications are lacking. The formulation of such requirements constitutes a pivotal element in the advancement of injection technologies and the establishment of a design and technical framework. **Materials and methods.** A rigorous analysis was conducted to ascertain the primary deformation parameters of stabilized soil treated with grouting mixtures. This restructuring of the soil mass enhances its properties. The performance of fast-setting polymer systems was also analyzed. The subjects' rapid development of strength is indicative of their suitability for emergency operations. **Results and Conclusion.** An analysis of the results indicates that grouting mixtures can enhance the properties of soil masses, suggesting the efficacy of such technologies, even in complex engineering-geological settings. These findings imply that injection methods are practically applicable to a wide range of weak soils.

KEYWORDS: construction, injection technologies, microstructure, soil-concrete, geotechnical mass, deformation characteristics, ultrafine binder, polyurethanes

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Формирование требований к инъекционным составам для повышения характеристик грунтов методами инъекционных технологий

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АННОТАЦИЯ

Введение. Геотехническая среда является динамической системой, основные показатели которой обеспечивают основные показатели надежности и безопасность работы строительных конструкций зданий и сооружений. Ухудшение свойств грунтов вследствие природных или техногенных причин приводит к непроектным параметрам и требует защитных мероприятий в виде закрепления (усиления) грунтов с формированием объемного геотехнического массива, в котором микроструктура обработанного грунта частично или полностью заполняется инъекционной смесью, обеспечивая повышенную связность и деформационные характеристики относительно первоначальных показателей. Инъекционные методы активно используются для решения широкого спектра возникающих геотехнических задач в виде стабилизации и повышения характеристик грунтов полимерными или минеральными составами. Однако многие требования к таким составам не представлены или даны в общем виде, отсутствуют многие методики, предпосылки расчетных обоснований. Формирование таких требований является важным фактором для развития инъекционных технологий и формирования проектно-технической базы. **Материалы и методы.** Проводился анализ определения основных деформационных показателей закрепленного грунта, обработанного инъекционными смесями, за счет перестроения структуры грунтового массива, имеющего повышенные характеристики. Также анализировалась работа быстротвердеющих полимерных систем, преимуществом которых является быстрый набор прочности, что позволяет их применять при аварийных работах. **Результаты и выводы.** Анализ результатов повышения характеристик обработанных инъекционными смесями грунтовых массивов позволяет считать инъекционные технологии эффективными даже в сложных инженерно-геологических условиях и практически применимыми в большинстве типов слабых грунтов.

КЛЮЧЕВЫЕ СЛОВА: строительство, инъекционные технологии, микроструктура, грунтобетон, геотехнический массив, деформационные характеристики, ОТДВ, полиуретаны

ИСТОЧНИКИ ФИНАНСИРОВАНИЯ НАУЧНОЙ РАБОТЫ, РЕЗУЛЬТАТОМ КОТОРОЙ СТАЛА ПУБЛИКАЦИЯ: Данная работа выполняется в рамках реализации Программы развития федерального государственного бюджетного образовательного учреждения высшего образования «Национальный исследовательский Московский государственный строительный университет» на 2025–2036 годы.

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INTRODUCTION

The safety of buildings and structures, in terms of their load-bearing capacity and stability is contingent upon the characteristics of the underlying soil. Deterioration of soil properties can be attributed to natural or anthropogenic factors, including changes in loads, vibrations, filtration, and water saturation. Such deterioration can result in abnormal behavior of both structures and soil mass [1, 2]. This abnormal behavior can potentially lead to a loss of stability, the occurrence of deformations, settlements, tilts, and deflections [3]. In certain circumstances, it may be imperative to declare a structure unfit for occupancy, prohibit public access to the construction site, and expeditiously implement safety measures (see Fig. 1).

It is imperative that possible changes in soil properties [4] are given full consideration during the design process of both the structure itself and the surrounding development. The study and prediction of potential soil degradation [4, 5] must be conducted with full consideration of the main contributing factors, while eliminating or minimizing the impact of the process that has the most negative effect. As illustrated in Table 1, the principal factors that lead to the degradation of soil properties are

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Fig. 1. A building with settlement exceeding regulatory limits (deterioration of the soil foundation, impact of new construction near the building). Vertically sloping cracks on the walls, longitudinal cracks in the floor slabs

Table 1. Major factors, deteriorating soil properties

Factor	Impact	Impact on the Soil Mass
Type I Factor	Mechanical impact on the soil mass: IA – static impact, IB – dynamic impact	Changes in density, reduction in soil particle cohesion, and changes in deformation parameters
Type II Factor	Physical effects on the soil mass: thermal, electrical, chemical, etc.	Changes in the aggregate state of water within pores (including decompaction), heaving and swelling, and increased corrosion activity
Type III Factor	Transformation of the soil skeleton due to physico-chemical factors (including biochemical effects)	Changes in density, soil particle cohesion, and deformation parameters

presented, with these factors divided into three categories according to the nature of the impact: mechanical, physical, and physicochemical impacts.

The most prevalent cause of soil property deterioration is the waterlogging of the soil mass due to changes in surface runoff parameters, leaks from utility lines, disruptions to hydrological conditions, the impact of new construction, and karst hazards [1, 6].

In the event that soil properties deteriorate beneath existing buildings and structures, the task of restoring the required bearing capacity of the foundation [7, 8] involves ensuring that the foundation's original properties are maintained [9, 10] or even significantly improved [11, 12] by creating a geotechnical mass [13, 14] within the most deformable elements of the compressible layer, due to the presence of additional settlements. Advancements in injection technologies have enabled the restoration of the properties of virtually all soil types [15, 16]. Moreover, if necessary, compensatory injection technology can be employed to compensate for settlements.

The injection of grouting mixtures into the soil mass results in the enhancement of weak soils through various mechanisms:

1. The injection of ultrafine micro-binders the injection mixture consists of an aqueous suspension containing mineral particles (ultrafine particles-products of hydraulic binder separation with $d95 = 5–18$ µm, including up to 10% of finer nanoparticles with diameters less than 100 nm [17, 18], dispersed metakaolin, mineral microfillers, and combinations thereof) [19, 20]. Injection (see Fig. 2) can be performed in a saturation mode (with maximum filling of the soil pore space) or by the hydraulic fracturing method [16, 21]. In this process, the grouting mixture introduced into the soil gradually hardens and gains strength [16, 22]. It is hypothesized that the strength continues to increase over many years, reaching significant values relative to standard strength indicators at 28 days of age.

2. In the context of the injection of polyurethane-based polymer mixtures [23, 24], it is imperative that the polyurethane mixtures are classified according to their foaming coefficient. It is hypothesized that at low foaming coefficients, the process primarily involves the impregnation of the soil mass [25, 26], with the individual soil particles being bound by the injected polymer mixture (typical for sandy soils) [27, 28], or hydraulic fracturing

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Fig. 2. Soil stabilization by injection (collar technology) – injector installation shown

with overall compaction of the soil mass (similar to the ultrafine binder hydraulic fracturing cementation method), which is more typical for clayey soils [29, 30]. In the context of utilizing polyurethanes characterized by elevated foaming coefficients [31, 32], the prevailing mechanism of stabilization is hypothesized to be the enhancement of soil particle compaction characteristics (a consequence of the material's augmented volumetric expansion) [33, 34]. As demonstrated in studies [23, 35], the formation of a solid mass has been observed to occur as a consequence of partial hydraulic fracturing and impregnation [36, 37]. However, this phenomenon occurs to a lesser extent in comparison to polyurethanes that possess low foaming coefficients. [38, 39]. It has been established through numerous studies [21, 32, 40] that the microstructure of sandy soil injected with a polyurethane composition (in which the size of polyurethane macromolecules ranges from 0.4 to 2.0 nm, given that this is a polymer with variable chain length, with the total length of a macromolecule reaching 1,000 nm or more) constitutes a conglomerate in which part of the mass exhibits enhanced properties due to the binding of individual particles by the polymer, and another part due to the compaction of soil particles, even without polymer binding.

The present article did not analyze the jet grouting method, since this essentially constitutes soil replacement (the erosion of a cavity by a high-pressure jet, with complete or partial replacement by cement mortar) and is a variation of the pile foundation system. Furthermore, the implementation of jet grouting technology has been observed to induce substantial alterations in the stress distribution within the soil mass. This observation underscores the necessity for caution when employing this method in proximity to existing structures.

Studies by the authors [12–22, 23–40] note the efficacy of grouting methodologies for soil stabilization, utilizing polymer and mineral formulations in accordance with the regulatory framework delineated in SP 22.13330.2016 "Foundations of Buildings and Structures" and SP 45.13330.2017 "Earthworks, Basements, and Foundations." These documents address the utilizations of contemporary microcements, namely ultrafine binder, polyurethane, epoxy, and acrylate compositions, within their designated primary domains of application. However, regulatory sources do not provide requirements for the parameters of injection compounds, and for the most part, they do not specify clear parameters for technologies

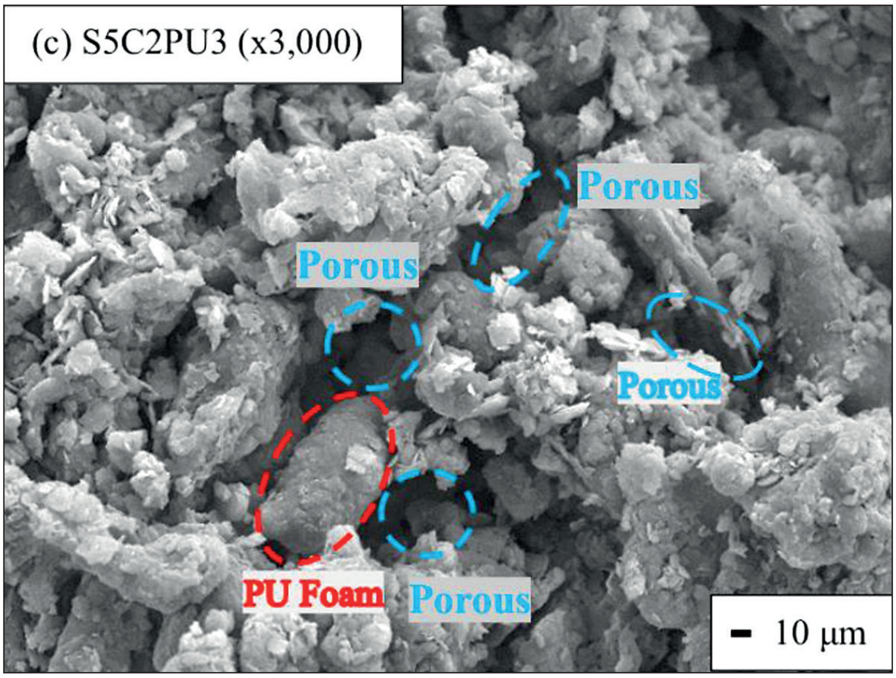

Fig. 3. Soil binding by a polyurethane mixture at the microscale; the polyurethane mixture locally fills the pores in the soil [40]

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or requirements for the materials serving as the basis for the grouting mixture.

A review of the extant regulatory and scientific and technical literature reveals a paucity of unambiguous, clear recommendations regarding the application of soil stabilization technology or the selection of the optimal grouting mixture formulation. It is hypothesized that designers possess a wide range of expertise and that scientific and technical standards are available when selecting the optimal parameters.

MATERIALS AND METHODS

The study utilized a range of data on completed underground construction projects and laboratory experiments, which demonstrated the effectiveness of grouting methods for soil stabilization using polymer and mineral compositions in accordance with design specifications. In the absence of regulatory requirements for polyurethane compounds, the requirements were formulated based on the requirements for two-component polyurethane resins from Group AG according to GOST 33762-2016. Group AG includes grouting compounds with an adhesive-sealing closure, which form a polymer-based (non-structural) seal within the crack cavity with a resilient, elastic, and watertight structure, adhesively bonded to the concrete structure, capable of withstanding the effects of crack movement and water pressure. This group consists of reactive polymer compositions of the injection type, based on two-component polyurethane resins (isocyanates and polyols). These compositions exhibit an adhesion to concrete of at least 1.0 MPa. They are designed for the elastic and rigid filling and sealing of cracks, construction joints, and other permeable defects in concrete. Polyurethane compositions with low foaming coefficients (Kfoam) have not been the focus of investigation, despite the existence of studies noting the possibility of such applications. The reason for this is that their analogues are ultrafine binder mineral mixtures, the majority of which require less complicated equipment and a wide range of formulation options using the same material.

In the field of construction, the primary function of polyurethanes is threefold: first, to rapidly contain pressurized leaks; secondly, to eliminate seepage in the soil mass, including high-pressure seepage; and thirdly, to fill large voids in soils, primarily during emergency operations.

In the field of soil stabilization, a two-component polyurethane system, comprising isocyanates and polyols, has emerged as the predominant approach [26–32]. These systems possess a three-dimensional branched block structure, characterized by a substantial proportion of hydrophobic urethane groups that are intricately cross-linked (see Fig. 4). This structural intricacy confers upon the resulting polymers exceptional chemical stability and outstanding mechanical properties.

The expansion of the polyurethane composition occurs through the reaction of isocyanates with water (carbon dioxide is the main component of the gases released) according to a reaction of the type:

$$R{-}NCO + H_2O \rightarrow R{-}NH_2 + CO_2\uparrow.$$

The carbon dioxide (CO_2) released during this process forms bubbles, thereby creating a cellular structure. The judicious selection of components in chemical production enables the control of the maximum potential volume of gas release by adjusting the foaming criteria and, consequently, the porosity of the resulting system.

The use of the ultrafine micro-binder (CEM I 52.5 separation product) with a d95 parameter of 6 µm was investigated as a mineral-based grouting mixture (95% of the particles have an average particle diameter of no more than 6 µm, with up to 10% of microparticles having a diameter of less than 100 nm) and a specific surface area of 20,000 cm^2/g. A distinctive feature of grouting mixtures based on ultra-fine-dispersed micro-binders is their high permeability, low sedimentation and water separation rates, and the ability to form uniformly three-dimensionally consolidated soil masses when using impregnation injection technology (see Fig. 5, case a). When complete, high-quality injection impregnation occurs for ultrafine binders with the diameter of the largest particles being 5–20 times smaller than the nominal diameter of the soil pore channel through which the grouting mixture passes. In this process, the presence of nanoparticles in the ultrafine binder (to fill the finest pores and capillaries) and the exclusion of large ultrafine binder fractions (which have the capacity to block pore channels, thus halting the saturation process with the

$$\underset{\text{isocyanate}}{R\text{-}N{=}C{=}O} \quad + \quad \underset{\text{polyol}}{R1\text{-}CH2\text{-}OH} \quad = \quad \underset{\text{polyurethane}}{R\text{-}[\text{-}NH\text{-}\overset{\overset{O}{//}}{C}\text{-}O\text{-}]\text{-}CH2\text{-}R1} \quad + \quad \underset{\text{warmth}}{\Delta}$$

Fig. 4. Structure formation of polyurethanes based on isocyanate mixtures; the mechanism of macromolecule formation involving urethane groups

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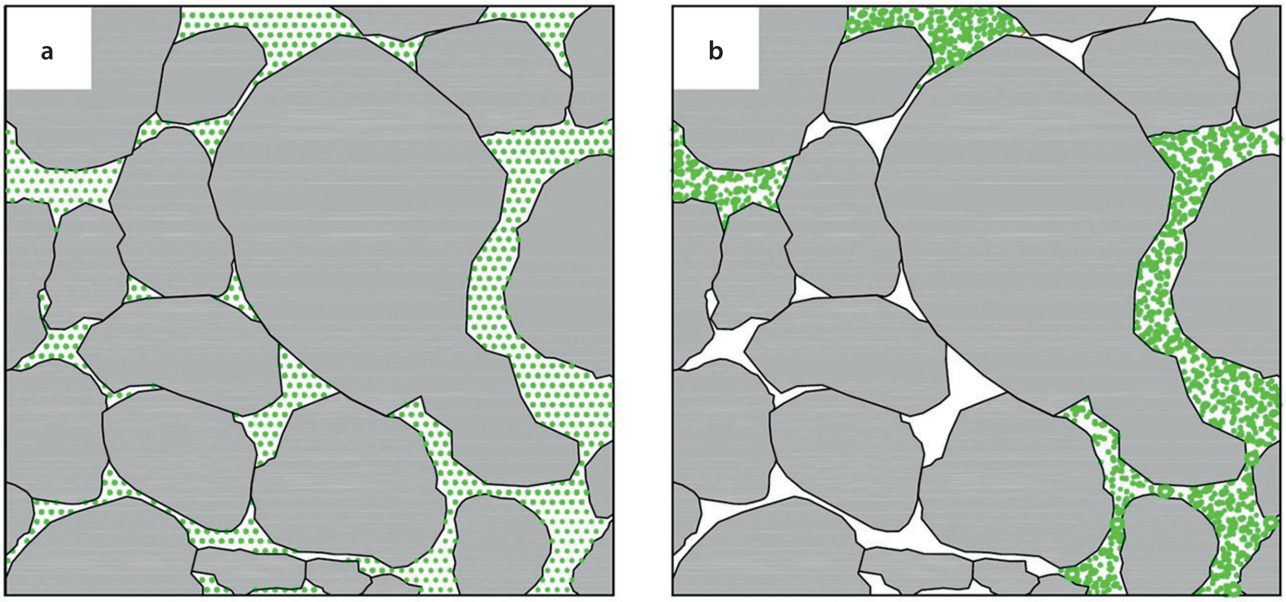

Fig. 5. Binding of sandy soil with an ultrafine binder solution at the microlevel: a – the ultrafine binder has the correct particle size distribution – the grouting mixture penetrates even the smallest pore channels; b – the ultrafine binder particle size distribution is not fine enough – only the largest pores are filled with the grouting mixture

grouting mixture) play an important role in the complete filling of the pores.

The foundation behavior was simulated using the Plaxis 3D geotechnical software package, employing the "Plastic" design method for elastic-plastic analysis. This analysis type involves defining the loading through the manipulation of various parameters. These include the load combination, stress state, weight, strength, and stiffness of the foundation soil clusters. In certain instances, probabilistic elevated characteristics can be specified when reinforcement is necessary. Alternatively, structural elements can be activated or deactivated to simulate the construction process.

The properties of stabilized soils were analyzed for compliance with design specifications:

- for injection impregnation- by testing core samples drilled from the stabilized soil (see Fig. 6) to determine uniaxial compressive strength or the modulus of deformation (triaxial compression method).
- for injection fracturing and compaction- by probing the stabilized mass to determine the modulus of deformation (see Fig. 7).

The following studies were conducted:

At Site No. 1 (project objective: to bring the parameters to values corresponding to the design soil resistance of the foundation, R0 > 100 kPa, with a modulus of deformation of 15–25 MPa). The soil to be stabilized consisted of water-saturated loamy-sandy soil containing

Fig. 6. Uniaxial compression test of a cut core of stabilized soil

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Fig. 7. Investigation of the properties of stabilized soil using the probing method

construction debris in the form of crushed brick, concrete fragments, asphalt, and wood residues; it was moderately compacted and contained layers of silty alluvial sand. The proposed technology involves the injection of ultrafine binder solutions with the highest degree of dispersion at high water-to-binder ratios.

At Site No. 2, the foundation subgrade consists of medium-density silty sand. To stabilize the subgrade and prevent excessive settlement, grouting with a polyurethane system was recommended. The design criterion for the safety of the structure's continued operation was to achieve a modulus of deformation in the range of 25–40 MPa.

At Site No. 3, the objective was to stabilize the soil by increasing the modulus of deformation to values in the range of 60–100 MPa. The EGE layer that was subjected to grouting consisted of heterogeneous fill soil, predominantly reworked sand of medium grain size, which was moist, with interlayers of loam and up to 20% inclusions of broken brick and gravel. The method employed involved the utilization of ultrafine binder solutions for grouting purposes.

RESULTS

In order to address the challenge of improving soil properties, the authors previously analyzed international and domestic experience with soil stabilization using injection methods [12–22, 23–40], identifying key relationships, trends, effectiveness analyses, and criteria for applicability. The most significant steps in ensuring the load-bearing capacity of structures are the creation of a design model (see Fig. 8) that illustrates the behavior of the foundation and structures under actual and, subsequently, predicted settlement values based on data from geological and auxiliary surveys.

In accordance with the specified settlement standard, the properties of stabilized soils were evaluated primarily based on the modulus of deformation, which exhibited higher values than the initial characteristics.

The processes under study, involving the injection of mixtures into dispersed soils, differ from the most extensively studied injection mechanisms in rock soils. The latter generally have significant voids, cracks wider than 5 mm, and a high degree of permeability. Furthermore, significant disparities emerge in the context of injection into sandy and clayey soils, attributable to the markedly divergent pore structures characteristic of these two soil types. The most predictable outcomes are achieved

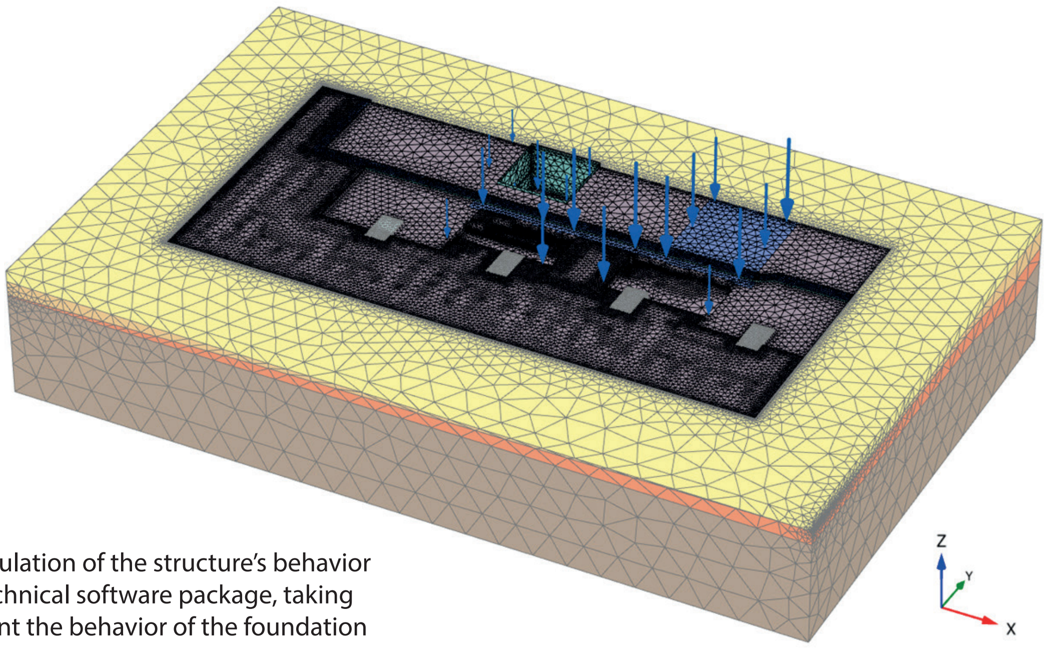

Fig. 8. Simulation of the structure's behavior in a geotechnical software package, taking into account the behavior of the foundation

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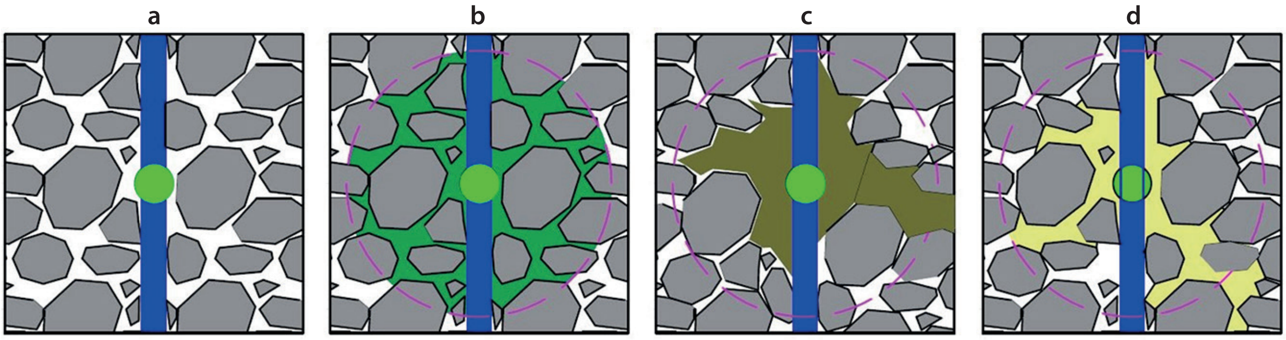

Fig. 9. Improving the properties of dispersive sandy soil can be achieved through the following methods: a – soil's original natural structure; b – the impregnation injection method (an ultrafine binder-based grouting mixture fills the pore space without displacing the grains); c – the compaction injection method (the polyurethane mixture expands as it is injected into the soil, attempting to displace the soil from the injection point due to injection pressure and the expansion of the mixture); d – the hydraulic fracturing method (the mineral mixture fills large pores, partially displacing the soil)

through the injection of fluids into sandy soils; the stabilization of clayey soils has been less extensively studied and can vary significantly depending on the natural characteristics of the soils and the technologies employed.

In light of the specific nature of soil stabilization work (the need to stabilize the soil mass and prevent excessive deformations), and in view of the frequently observed progressive settlement of buildings, it is often necessary to make prompt decisions before a full range of surveys and studies of the characteristics of the soils to be stabilized can be completed. For instance, at sites No. 1–3, the permeability coefficient of EGE requiring stabilization was not investigated; the injection parameters were determined at test sections. This parameter is indicative of the rate of water seepage through the soil at a unit hydraulic gradient, thereby characterizing the soil's permeability. This is a particularly salient consideration in the context of injection grouting technology. Conversely, in conditions of heterogeneous, unstable soils (the primary cause of settlement deformations), all soil characteristics can vary significantly across different stabilization sections, resulting in different pressures, specific flow rates, and the need to adjust the mixtures during stabilization work.

At Site No. 1, due to the low soil permeability, ultrafine binder mixtures with a particle size distribution of d95 = 6 μm were selected, with an initial W/C ratio of 4.5, subsequently adjusted to 3–3.5. The grouting process was executed at a standard pressure of 0.4–0.5 MPa, with a specific flow rate of 0.5–1.5 L/min. It was observed that as the specific flow rate increased, the pressure exhibited a sharp rise to 0.9-1.1 MPa. This necessitated a subsequent reduction in the mixture's flow rate. In certain injection horizons, the pressure was elevated initially, which was likely the reason why the injection point was predominantly located within a clayey structure. Furthermore, observations were made of horizons where injection pressure was reduced; a possible cause for this phenomenon was identified as the presence of a layer of water-saturated alluvial silty sands. During the course of field testing on pilot sites, it was observed that in areas stabilized with mixtures having a W/C ratio of 4.5, the strength development of the soil-concrete mixture was extremely slow. The decision was thus taken to reduce the W/C ratio to 3–3.5. In addition, various options for using plasticizers and setting accelerators were also considered, but ultimately their use was not approved. It was observed that at a W/C ratio of 4.5, the strength development of the mass was found to be significantly delayed during the initial phases of hardening, and the process of taking core samples was rendered challenging. It was established that, at W/C ratios of 3.0 and 3.5, the stabilized soil met the design specifications. Prior to the commencement of primary construction operations (approximately 180 days following the initiation

Table 2. Analysis of data on the properties of stabilized soil at Site No. 1. Deformation modulus at various stages of hardening

W/C of mixture	E, MPa (28 days)	E, MPa (56 days)	E, MPa (180 days)
4.5	–	–	16.0
3.5	19.2	23.7	24.9
3.0	20.8	25.2	29.7

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of grouting), samples were systematically collected from areas deemed to be potentially problematic.

At Site No. 2, the injection of a polyurethane compound was recommended due to the presence of silty sand, which exhibited low permeability. This condition would have rendered conventional injection grouting challenging. During drilling operations, variations in soil density were observed, manifesting as differences in drilling speed and the forces required to propel the drill string through the soil. When the expanding polyurethane mixture is injected into the soil, a process of soil compaction occurs (with the mixture localized at the injection point), accompanied by partial injection-induced soil saturation (though this process is less common in silty sands) and hydraulic fracturing (along weak soil layers). The specific flow rate varies significantly across different work sites; in areas with loose, unconsolidated sands, the flow rate is higher, and material localization at the injection point is greater than in areas with densely packed sands. Probing data collected 1 day after the completion of work showed an increase in the modulus of deformation of the injected mass to 25–28 MPa.

At Site No. 3, the primary challenge was the inherent nature of the anthropogenic soil structure, which comprised broken bricks, gravel, various anthropogenic inclusions, and interlayers of clayey and organo-mineral soils. However, the acceptable permeability values thus obtained permitted the successful implementation of injection-based soil stabilization using ultrafine binder solutions. The ultrafine binder was utilized with a particle size distribution of d95 = 6 μm and a water-to-cement ratio (W/C) of 1.5–2.5. The injection process was executed at a standard pressure ranging from 0.1 to 0.4 MPa, with a specific flow rate of 2.5 to 5.5 L/min. During the drilling phase, a certain amount of voids was observed. Subsequently, during the primary injection phase, it was noted that the injection pressure was extremely low (less than 0.1 MPa, even at high specific flow rates). This necessitated the introduction of an additional cementation stage at the "foundation-soil" interface, utilizing conventional Portland cement-based mortars to fill the large voids. Furthermore, during the course of the work, a high overall prevalence of numerous layers of organo-mineral soils within the anthropogenic strata was observed, which subsequently resulted in reduced hydration kinetics of the grout mixtures within the soil mass and a slower rate of strength development in the geotechnical mass. The EGE layer that was subjected to grouting treatment achieved the target values for the deformation moduli, although not within the designated timeframe. Non-design soil conditions were taken into account (the presence of voids and the overall high porosity of the mass, an anthropogenic layer with organo-mineral inclusions, increased water saturation of the mass during the summer rainy season, etc.).

In the course of providing scientific and technical support for various projects, including as part of the implementation of the 2025–2036 Development Program of the Federal State Budgetary Educational Institution of Higher Education Moscow State University of Civil Engineering (National Research University), the following observations were made:

1. In soils exhibiting high permeability, the presence of voids, and a well-developed pore structure – such as those found in fine-grained sandy soils – the most optimal method is injection impregnation using ultrafine binder solutions. These solutions are capable of saturating the intergranular porosity even in fine and silty sands, thereby forming a geotechnical mass with enhanced properties.

2. In soils exhibiting low permeability, the implementation of injection technology employing hydraulic fracturing with ultrafine binder or polyurethane-based compounds is a viable option. This process has been shown to fill the largest pores and generally compact the soil mass, thereby improving its deformation characteristics. However, the expansion of expansive polyurethane under different stress conditions of the soil mass remains an unstandardized and unexplored factor.

3. The set of strength parameters for a geotechnical formation is contingent on a multitude of factors that are frequently challenging to account for during construction, including moisture content, porosity (type and general values), temperature, soil homogeneity, and changes in these parameters during the construction period. It is also pertinent to acknowledge the relevance of SP 446.1325800.2019, entitled "Engineering-Geological Surveys for Construction. General Rules for Work Performance" stipulates that the distance between geological boreholes should not exceed 20-25, even under complex engineering-geological conditions (Category III), which is often a priori less than the length of the stabilization

Table 3. Analysis of data on the properties of stabilized soil at Site No. 3. Deformation modulus at various stages of hardening

W/C of mixture	E, MPa (28 days)	E, MPa (42 days)	E, MPa (56 days)
2.5	–	–	61.1
1.5	48.7	65.8	89.7

section. Furthermore, such geological data provide only general information.

4. In the execution of soil grouting operations, it is imperative to consider the potential existence of uncompacted areas and voids within the soil mass. In such instances, additional backfill grouting may be necessary to ensure the integrity of the soil mass. Additionally, the presence of organo-mineral inclusions, which are particularly prevalent in synthetic soil, must be taken into account. These inclusions can impede the rate of strength development in the geotechnical mass, necessitating careful consideration and management.

5. The heterogeneity of soils with varying pore structures results in different absorption rates per 1 m^3 of the soil mass being stabilized and different grouting parameters. In the context of finer-pored soils, the implementation of grout mixtures with enhanced penetrating capabilities, the utilization of low specific flow rates, and the employment of specialized equipment with automatic control systems, particularly in the context of impregnation grouting, are imperative. In the context of hydraulic fracturing injection in heterogeneous soils, it is imperative to maintain consistent injection volumes to ensure a more or less uniform distribution of hydraulic fractures and compaction within the forming geotechnical mass. This approach ensures the absorption of the injected fluid at the lowest possible injection pressures.

6. The most accurate characteristic of ultrafine binder mixtures, which allows for prediction of the parameters of injection grouting, is the particle size distribution index of the ultrafine micro-binder-d95, and in some cases, d98. The total specific surface area, as determined by the Blaine method for ultrafine binder, as outlined in several regulatory documents, serves as an indirect indicator. It does not guarantee impregnation injection, even when the stipulated specific surface area is attained. This is due to the significance of a balanced particle size distribution for ultrafine binder, which can be accomplished through the utilization of a blend of fine and coarse particles. Furthermore, during the process of injection grouting, the presence of coarse particles becomes impeded within the pore channels, consequently hindering the progression of soil saturation.

7. There is a necessity to update regulatory, technical, and advisory standards. It is evident that the implementation of successful projects is predominantly facilitated by scientific and technical support, in conjunction with the continuous adjustment of injection parameters and the regulation of grouting mixture properties.

– The characteristics of stabilized soil and polymer grouting mixtures, as well as the requirements for them, are not described; there is no justification for their use or comparison with other compositions
– Issues regarding the durability of mixtures (including in soil) are practically not addressed, although a loss of bearing capacity in previously stabilized soil can lead to catastrophic consequences

Given the lack of standardization and design methods, composition selection procedures, and work monitoring protocols, research is needed on the properties of grout mixtures and stabilized soils, along with the development of further recommendations and the refinement of methodologies through field testing at physical sites.

CONCLUSION

The results of the research conducted as part of the scientific and technical support on soil stabilization using low-pressure injection methods indicate that the properties of soil foundations can be enhanced through the injection of impregnating mixtures based on ultrafine binder and the compacting of polyurethane expanding mixtures. A number of parameters for grouting mixtures have been identified that are not currently reflected in the technical standards, regulations, or methodological literature.

The specifications of stabilized soils are contingent on the properties of the original soil mass, which frequently necessitates a denser borehole grid during surveys or detailed recommendations for the selection and adjustment of grouting mixtures, taking into account the injection pressure at different specific flow rates.

Researchers at Moscow State University of Civil Engineering (MGSU) specialize in conducting scientific and technical support in the field of design and construction in complex engineering-geological conditions. Through meticulous analysis and experimentation, they have developed methodologies for the selection of grouting parameters and the adjustment of injection system properties. These methodologies enable the precise control of the characteristics of the resulting geotechnical massif.

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