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Technological Features of Foundation Construction Using Vibro-Reinforced Soil-Cement Piles

The article examines the technological features of foundation construction using vibro-reinforced soil-cement piles. The technology is based on the bore-mixing method, which allows for pile formation without soil excavation, utilizing the existing soil as the main component of the soil-cement mixture. The use of vibro-reinforced soil-cement piles significantly increases the load-bearing capacity of foundations, reduces labor intensity in the construction process, and ensures the stable performance of the foundation in complex engineering and geological conditions. The article explores the specifics of the technological process of manufacturing vibro-reinforced soil-cement piles, particularly their formation, vibro-compaction, and the use of a high-frequency vibrator when embedding the reinforcement cage. It has been proven that the physical and mechanical properties of soil-cement piles, such as compressive strength, improve when deep vibrators are used in pile installation. A comparative analysis of vibro-reinforced and conventional soil-cement piles has demonstrated a significant increase in the load-bearing capacity of vibro-reinforced piles, which allows for a reduction in their number within foundation structures and leads to lower construction costs. Additionally, the article compares the soil cementation methods Jet Grouting, Pressure Grouting, and Deep Soil Mixing, which are used to improve soil bearing capacity and reduce deformations. Each of these technologies has its own characteristics that determine their effectiveness under different conditions. The advantages and disadvantages of each method are examined, including the ability to reach great depths, cost-effectiveness, and localized application.

Keywords: soil-cement piles, foundations, vibration reinforcement, vibration compaction, manufacturing technology.

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Introduction

Modern construction requires the use of reliable and efficient foundation technologies that ensure the stability of buildings and structures in challenging geotechnical conditions. With the advancement of construction technologies, there is a growing need for methods that strengthen weak soils and improve their physical and mechanical properties. One of the most effective solutions is soil-cement piles, which combine the advantages of the deep mixing method and deep vibro-compaction.

Soil-cement piles are widely used for building foundations in areas with low soil-bearing capacity. Their construction methodology significantly reduces settlement, enhances foundation stability, and minimizes the risks of uneven deformations. The core principle of this technology involves deep mixing of soil with a cement slurry without removing the soil, ensuring a uniform distribution of material and forming a strong soil-cement element.

Beyond improving the physical and mechanical properties of the soil, this technology offers several other significant advantages. It reduces the time and cost of foundation works, minimizes environmental impact by limiting earthworks, and increases the durability of structures. Additionally, the deep mixing method effectively prevents void formation and soil subsidence, making it particularly relevant for construction in seismically active regions or on unstable terrains.

This article examines the features of soil-cement pile technology, its main stages, quality control methods, and comparative efficiency in relation to other foundation construction techniques.

The design and calculation of foundations on soil-cement piles are based on modern regulatory documents, such as Eurocode 7 [1], which defines the general principles of geotechnical design.

Review of the research sources and publications.

Modern scientific studies in the field of soil-cement pile installation using deep mixing and vibro-compaction methods focus on increasing technological efficiency, reducing material consumption, and ensuring structural reliability under weak soil conditions. In particular, works [10,11] analyze the economic feasibility and design features of vibro-reinforced soil-cement piles, demonstrating their advantages in reducing the number of foundation elements without compromising load-bearing capacity.

Monographs [7,8] provide a detailed examination of the deep mixing method and its application under various engineering and geological conditions, including loess and sandy soils. Study [9] emphasizes the role of vibro-reinforcement in ensuring pile integrity and base stability.

The regulatory framework, including Eurocode 7 [1], Eurocode 2 [2], and standard EN 1536 [5], sets the requirements for the design and execution of special geotechnical works, defining technical criteria for quality control and structural reliability assessment.

Study [13] presents international experience with the Deep Mixing method for ground improvement, summarizing research findings and practical implementation across different countries.

Definition of unsolved aspects of the problem

Currently, there are no clearly defined standards for the installation technology of vibro-reinforced soil-cement piles in construction practice. As a result, various technical solutions are employed, leading to inconsistencies in the execution of works. This variability complicates quality control and reduces the predictability of results. Moreover, inconsistencies in the selection of process parameters-such as mixing speed or reinforcement insertion method-can negatively affect the strength and stability of the piles. Consequently, this may reduce foundation reliability, which is particularly critical in complex soil conditions or under high loads.

Therefore, there is a pressing need to develop a unified construction methodology that ensures consistent quality, adequate load-bearing capacity, and long-term durability of foundations.

Problem statement

Considering the identified lack of standardized approaches to the construction of soil-cement piles, the main objective of this research is to analyze and improve the technological process of their installation.To achieve this objective, the following tasks were set within the scope of the study:

- to describe the main stages of the technological process of deep mixing and insertion of the reinforcement cage using a deep vibrator;
- to present a sequence of quality control operations at all stages of the technological cycle.

Basic material and results

The essence of the deep mixing technology for soil-cement production lies in the fact that during the drilling of a borehole, the natural soil is loosened without being removed from the borehole. A water-cement slurry is pumped through a swivel equipped on the drilling rig into the zone of loosened soil, where it is thoroughly mixed with the soil using a working nozzle. The loosening of the soil, the supply of the cement slurry, and its mixing with the soil are carried out along the entire length of the soil-cement pile. Once the mixture hardens, a strong soil-cement element is formed, which functions as a pile in the soil. The compressive strength of the soil-cement pile usually reaches up to 10 MPa.

The process of vibratory reinforcement of the pile with a reinforcement cage is carried out immediately after mixing. A deep vibrator is inserted into the cage and secured. The cage is lifted, centered, and then gradually lowered. High-frequency vibrations facilitate the immersion of the cage to the design depth. Deep vibratory compaction of soil-cement piles is performed immediately after the reinforcement cage is installed. The high-frequency deep vibrator, submerged to the design depth, is gradually raised to ensure reverse compaction. The vibration process continues until the entire pile shaft material is fully compacted.

The main stages of soil-cement pile construction, from preparatory work to quality control, will be examined in detail below.

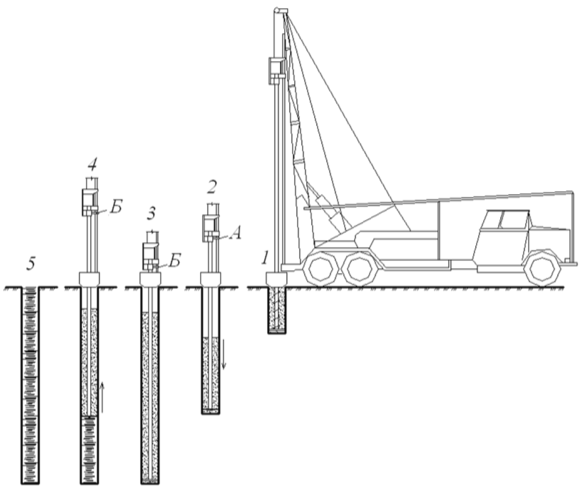

Figure 1. Technological scheme for the construction of soil-cement piles using the Deep Soil Mixing method: 1 – creation of a shallow pit; 2 – penetration of the mixing auger and conversion of the soil into a fluid state; 3 – cavity filled with soil of a fluid consistency; 4 – lifting of the mixing auger and injection of the water-cement grout; 5 –pile ready for reinforcement cage installation: А – water; Б – grout.

Before installing soil-cement piles, it is recommended to conduct field test trials on the adjacent construction site. The test should monitor the rotational speed and penetration rate of the auger. A trial installation of a soil-cement pile in field conditions should be conducted to verify that its physical and mechanical properties meet the specified design requirements.

The use of cement slurries and reinforcement of foundation elements must comply with Eurocode 2 [2], which regulates the design of concrete and reinforced concrete structures.

Various types of sands, loess, loess-like carbonate loams, and sandy loams are suitable for the production of vibratory-reinforced soil-cement piles. The content of water-soluble salts should not exceed 3%, including sulfate salts, which should be no more than 2%. The optimal pH level for soil-cement formation should be between 6 and 8.

Drilling begins by positioning the nozzle at the designated drilling point and lowering it into the soil through rotation. The water-cement slurry is supplied only after the nozzle is fully embedded in the soil. The design depth is achieved by continuous slurry supply using the deep mixing method. The mixing of soil-cement within the pile shaft continues until the material reaches a homogeneous state. Borehole drilling with auger extension starts with the first drill rod, which is equipped with a nozzle for breaking up the soil and mixing it with the cement slurry. The design depth of the borehole is achieved through the gradual addition of rods, which are connected with special couplings. During auger extraction, additional mixing is performed with the introduction of cement suspension. Several mixing cycles can be conducted per auger height to achieve a more uniform soil-cement composition.

Fig. 2. – Reinforcement Cage Immersion Scheme: 1 – reinforcement cage; 2 – deep vibrator.

When passing through loess sandy loams and loams above the groundwater level, water should be injected first instead of the water-cement slurry to create a homogeneous fluidized soil mass. The water-cement slurry is supplied during auger extraction. When drilling through water-saturated sands and clayey soils, the water-cement slurry is supplied immediately upon auger penetration.

The mixing efficiency of soil-cement depends on the rotation speed of the loosening tool. Higher rotational speeds improve the mixing process. The quality of soil-cement mixing is also influenced by the auger penetration speed. A lower penetration speed with a constant auger rotation rate results in finer soil loosening, which enhances the homogeneity of the mixture. During forward movement (penetration), the auger should operate at the following speeds:

- In sandy soils: 0.5 m/min, with 60 rotations per minute;
- In clayey soils: 0.3 m/min, with 60 rotations per minute.

The reverse movement of the auger and repeated penetration cycles should be performed at a speed not exceeding 1.0 m/min, ensuring vertical displacement per auger rotation of 16 mm at 60 rotations per minute.

A freshly installed soil-cement pile undergoes vibratory reinforcement immediately. The reinforcement cage is inserted into the soil-cement mixture while it is still in a fluid state. Initially, the cage is embedded under its own weight, and later it is driven further into the pile using vibratory action.

High-frequency vibrations enable the reinforcement cage to be embedded to the design depth. Deep vibro-compaction of soil-cement piles is carried out immediately after the completion of the reinforcement cage installation. A high-frequency deep vibrator, having been lowered to the design depth after the cage insertion, is gradually raised to perform reverse compaction. After the project-specified time, the vibrator is lifted by a distance equal to the sum of the working element length and twice the radius of influence. The vibration process continues until full compaction of the entire pile shaft material is achieved.

Reinforcement cages are manufactured from ribbed reinforcement bars of class A400C. The circular cross-section diameter of the cage must be 150 mm smaller than the pile diameter. The cage is installed immediately after the formation of the pile in soil-cement, which remains in a fluid consistency. At the initial stage, the cage is embedded under its own weight, and subsequently, under the influence of vibration.

During winter installation, when the ambient temperature is below 0°C, antifreeze additives should be added to the slurry to prevent freezing. The additive is mixed with water before preparing the water-cement slurry. At temperatures below -5°C, the water should be preheated. After pile installation in freezing conditions, insulation with thermal materials (such as dry sawdust, fiberglass, mineral wool, or polystyrene foam) is required for a curing period of seven days. Before foundation preparation, all insulation materials must be completely removed down to the undisturbed soil level.

Quality Control of Reinforced Soil-Cement Piles Since the production of soil-cement piles using the deep mixing method and their vibratory reinforcement are essentially concealed construction processes, quality control measures must be strictly observed to ensure the reliability of the produced soil-cement elements.

After construction, the quality of the soil-cement piles must be verified to confirm their compliance with parameters such as material homogeneity, strength, and dimensions. Quality control of piles installed by the deep mixing method is performed no earlier than seven days after installation, according to national construction standards [3,4], using core drilling of the pile body at 1-meter intervals along its depth, followed by strength testing of extracted cores. The number of control boreholes for core sampling should be at least 5% of the total number of piles.

The normative and calculated characteristics of soil-cement are determined in laboratory conditions and based on field studies, which include the adopted production technology for soil-cement.

The deep mixing method for soil-cement pile production complies with standard EN 1536 [5], which regulates the execution of specialized geotechnical works. Ensuring the quality of vibratory-reinforced soil-cement piles constructed using deep mixing technology is achieved through monitoring:

- Compliance of the cement type and grade with the project specifications;
- Accurate adherence to the design composition and consumption of the water-cement slurry;
- Operating parameters of the grout pump;
- Performance parameters of the deep mixer (rotation frequency, linear penetration speed, and number of passes);
- Operating parameters of the deep vibrator and the vibratory compaction regime;
- The vibratory embedding process of the reinforcement cage;
- The quality of the soil-cement mass and, if necessary, the load-bearing capacity of the soil-cement pile.

Let us consider the three most common soil cementation technologies: Jet Grouting, Pressure Grouting, and Deep Soil Mixing (DSM). All of these methods share a common purpose-improving the bearing capacity of the foundation and reducing its deformations. However, each method has its own specific features that determine its effectiveness under different conditions. Below is a comparison of these methods, highlighting their advantages and disadvantages.

Jet Grouting uses a high-pressure jet of cement grout to break up and mix the soil. This method is highly effective in clayey and sandy soils. Its main advantage is the ability to reach significant depths (up to 50 m or more) and form large-diameter piles. However, it requires complex equipment and involves high cement consumption due to significant grout losses. When piles are installed at great depths, reinforcement with cages is only carried out in the upper part of the pile.

Deep Soil Mixing (DSM) involves mechanically mixing the soil with cement grout, making it more economical compared to Jet Grouting. It is best suited for weak water-saturated soils, ensuring uniform strengthening at depths of up to 30 m. Although it produces a smaller diameter of the treated zone compared to Jet Grouting, this method ensures more stable cement usage with minimal losses.

Pressure Grouting involves injecting cement or another binding grout into the pores and cracks of the soil. This method is most effective when voids need to be filled locally or when fractured rock formations require stabilisation. Its main drawback is the slow execution speed, as the injection grout gradually permeates the soil, requiring additional monitoring.

Thus, it can be concluded that Jet Grouting is the most powerful and versatile method but requires complex equipment for high-pressure grout injection and leads to excess cement consumption due to the nature of the technology, where part of the cement mixture remains outside the pile body.

Additionally, if the soil layers along the pile depth vary in their physical and mechanical properties, the pile diameter may not be maintained consistently and can differ according to the soil parameters. In turn, Deep Soil Mixing is a more accessible and economical option for weak water-saturated soils, whereas Pressure Grouting is used for local applications, strengthening existing buildings and structures, and filling voids in the foundation.

Conclusions

The efficiency of soil-cement foundations primarily lies in the simplicity of their construction technology. The Deep Soil Mixing method benefits from the absence of heavy machinery, reduced transportation costs, and no dependency on the timely delivery of concrete mix.

An analysis of the technological process demonstrates that a proper approach to each stage of work significantly influences the quality of the final result. The application of modern soil stabilization methods contributes to the optimization of construction processes and enhances the reliability of structures.

The key stages of the soil-cement pile formation technology that affect the final outcome include:

1. Preparation stage – Analysis of the geotechnical conditions of the construction site, conduction of engineering and geological investigations, and selection of the optimal pile formation technology. Execution of trial testing and equipment inspection. Verification of the need to comply with special installation requirements, such as performing work in low temperatures.

2. Drilling boreholes – Execution of drilling operations to the specified depth, considering soil characteristics.

3. Injection of cement slurry – Pumping cement slurry under pressure into the borehole and mixing it with the soil to create a homogeneous mixture.

4. Mixing and compaction – Even distribution of the cement-soil mixture and its compaction to achieve the required mechanical properties.

5. Quality control – Testing the strength, homogeneity, and compliance of the piles with technical requirements.

6. Vibro-reinforcement – The process of inserting a steel reinforcement cage and compacting the soil-cement pile.

7. Hardening and curing – The process of the pile gaining strength up to the designed parameters.

Compliance with these technological processes ensures the reliability and durability of soil-cement piles.

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Технологічні особливості влаштування фундаментів із використанням віброармованих ґрунтоцементних паль

У статті розглянуто технологічні особливості влаштування фундаментів із використанням віброармованих ґрунтоцементних паль. Технологія базується на методі бурозмішування, який дозволяє формувати палі без вилучення ґрунту, використовуючи наявний ґрунт як основний компонент ґрунтоцементної суміші. Використання віброармованих ґрунтоцементних паль суттєво підвищує несучу здатність фундаментів, зменшує трудомісткість будівельного процесу та забезпечує стабільну роботу фундаменту в складних інженерно-геологічних умовах. У статті досліджено особливості технологічного процесу виготовлення віброармованих ґрунтоцементних паль, зокрема етапи їх формування, віброущільнення та застосування високочастотного вібратора під час заглиблення арматурного каркасу. Доведено, що фізико-механічні властивості ґрунтоцементних паль, зокрема міцність на стиск, покращуються при використанні глибинних вібраторів під час встановлення паль. Порівняльний аналіз віброармованих і звичайних ґрунтоцементних паль показав суттєве зростання несучої здатності віброармованих паль, що дозволяє зменшити їх кількість у конструкції фундаменту та знизити загальні витрати на будівництво. Крім того, у статті проведено порівняння методів цементації ґрунтів - Jet Grouting, Pressure Grouting і Deep Soil Mixing, які застосовуються для покращення несучої здатності ґрунтів та зменшення деформацій. Кожна з цих технологій має свої особливості, які визначають ефективність їх застосування за різних умов. Розглянуто переваги та недоліки кожного методу, зокрема здатність досягати значних глибин, економічність та можливість локального застосування.

Ключові слова: ґрунтоцементні палі, фундаменти, віброармування, віброущільнення, технологія виготовлення.

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