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Enhancing the compressive strength of soil-cement piles via drill string kinematics optimization in deep mixing

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Abstract. This study proposes an improved method for manufacturing soil-cement piles using deep soil mixing (DSM) technology to increase the bearing capacity and durability of foundations in soft soils. The relevance of the work is due to the need to increase the efficiency of the arrangement of bases and foundations in complex engineering and geological conditions, where traditional methods of soil reinforcement do not always provide the proper strength and homogeneity of the massif. The study presents a conceptual model of local compaction, which considers the borehole as a combined mechanical-hydraulic system, which allows for a more accurate description of the process of forming a soil-cement element and controlling its physical and mechanical properties. This approach integrates continuous injection of cement mortar with discrete reverse movements of the drill string every 350-400 mm, which ensures intensification of the mixing and compaction process of the soil-cement mixture throughout the depth of the borehole. This technological scheme contributes to the formation of a denser and more homogeneous structure of the material, reducing porosity and increasing the adhesive properties between soil particles and cement stone. Laboratory tests on clay, loam and sandy loam (cement content 10-20%) confirmed that stepped compaction increases the compressive strength by up to 47% (nearly 1.5 times), reaching 12.9 MPa *for clay and 15.2 MPa for sandy loam, which indicates the high efficiency of the proposed method.*

The results of the studies show that a compaction step exceeding 400 mm leads to structural heterogeneity and a decrease in the operational characteristics of piles, while the optimal interval provides maximum density and uniform distribution of stresses in the array. In addition, it was found that control of process parameters (tool lifting speed, mortar consumption, multiplicity of reverse movements) is of crucial importance for achieving stable results in field conditions. The technology reduces resource consumption by 25-35% due to the effective use of local soils, reduced cement and energy costs, and reduced work duration.

The proposed approach provides a resource-saving and environmentally sound solution for the construction of foundations and retaining walls in difficult geotechnical conditions, and also has the potential for widespread implementation in civil and industrial construction practice. The results obtained can be used in the development of regulatory recommendations and improvement of technological regulations for the performance of deep soil mixing works.

Keywords: soil-cement pile, Deep Soil Mixing (DSM), cement slurry, local compaction, drill string kinematics, bearing capacity

Introduction

Analysis of literary sources and problem statement. Recent studies [3-6] prove that the physical and mechanical characteristics of soil-cement critically depend on the technological operating parameters of the drilling rig. In particular, a recent study [1] demonstrated a direct relationship between the mixing energy transferred to the soil and the final unconfined compressive strength (UCS) of the stabilized mass.

The conventional pile manufacturing method involves continuous reverse rotation and lifting of the drill string with the simultaneous injection of cement slurry. Such continuous lifting kinematics often fail to provide a sufficient level of mixing energy in local areas, leading to the formation of under-compacted soil layers and uncontrolled filling of the borehole.

To address the problem of insufficient local compaction and a low degree of homogeneity, optimized drill string kinematics are proposed. The innovative approach consists of changing the reverse stroke algorithm: instead of continuous tool withdrawal, the upward movement of the string is carried out with stops every 350...400 mm of the borehole height. Meanwhile, the injection of the cement slurry occurs continuously.

Such a step-wise method allows for a radical change in the distribution of mixing energy. Periodic stops ensure the maximum possible penetration of the dosed cement slurry into the soil and its forced mechanical compaction directly under the expanding blades of the drill string. This creates conditions for additional cement saturation of both the remaining soil and the soil additionally cut from the borehole walls, significantly improving the structure of the final material.

Research aim and objectives. Although the conceptual mechanism of stepwise extraction of the drill string has been previously patented by the authors [2], its actual physical and mechanical effects on different types of soils have remained uncertain. The main objective of this study is to address the problem of structural heterogeneity in traditional deep soil mixing (DSM) by experimentally verifying this patented technology. In particular, this study aims to evaluate how optimizing the tool kinematics increases the local mixing energy, and presents the first comprehensive quantification of the strength increase of clay, loam, and sandy soils. In addition, the study scientifically substantiates the optimal kinematic parameters (step size) required for maximum local compaction.

Materials and methods

1. Characteristics of raw materials

To conduct the complex of experimental studies and physical modeling of the deep mixing process, three types of soil were selected: clay, loam, and sandy loam. The selection of these specific materials is justified by the fact that they are the most common components of structurally unstable foundation soils that require stabilization in actual construction practice. Portland cement was used as the inorganic binder to form the soil-cement matrix. To evaluate the effectiveness of the proposed technology at various levels of stabilizer saturation, the experimental program included three binder dosage variants: 10%, 15%, and 20% of Portland cement relative to the soil mass. Such a dosage range allowed for the construction of representative curves showing the dependence of strength on cement content.

2. Experimental design and modeling of manufacturing conditions

To identify the most critical factors influencing the structure formation conditions on the final strength of the soil-cement, samples were prepared in parallel in two series:

1) Control series (without compaction): modeled the conventional algorithm for manufacturing soil-cement piles with continuous mixing without creating additional compaction pressure.

2) Experimental series (with compaction): modeled the proposed innovative step-wise method of manufacturing piles with local compaction.

3) Algorithm of optimized kinematics and pile formation Physical modeling of the proposed method was based on modifying the kinematics of the working tool and included the following technological stages:

- Preparatory stage: drilling the initial borehole without bringing the soil to the surface.

- Expansion and mixing stage: additional expansion of the borehole was carried out by cutting the soil from its walls using the expanding blades of the drill string. Simultaneously, cement slurry was continuously injected into the borehole and intensively mixed with the soil.

- Step-wise compaction stage (core innovation): unlike conventional methods, the reverse movement (lifting) of the drill string was not continuous, but was carried out with strictly regulated stops every 350...400 mm of the borehole height. The slurry injection was not interrupted but occurred in a dosed manner during these stops (Table 1).

Table 1. Experimental design matrix

Test series	Modeling conditions (Tool kinematics)	Soils under investigation	PC content (% by soil mass)	Output controlled parameter
Series 1: Control (without compaction)	Traditional: continuous reverse movement of the drill string without additional stops for crimping	Clay	10	Compressive strength (MPa)
		Loam	15	
		Sandy loam	20	
Series 2: Experimental (with compaction)	Innovative: discrete movement with stops every 350...400 mm of height and dosed injection	Clay	10	Compressive strength (MPa)
		Loam	15	
		Sandy loam	20	

4. Local compaction mechanism and parameter control

The saturation of the remaining and cut soil with cement, as borehole as its compaction, was achieved specifically due to the stop of the drill string’s reverse stroke. This pause ensured the maximum possible penetration of the cement slurry under pressure and the physical compaction of the formed soil-cement mixture directly under the cutting blades. The duration of the saturation and local compaction process at each step was not fixed in time but was determined by the moment the flow of cement slurry into the formed mixture ceased. The time for resuming the upward movement of the drill string was recorded upon the termination of the slurry supply, which was monitored using the meter readings on the slurry pipeline. The limit parameters of the step were established empirically: stops of the drill string after lifting to a height of more than 400 mm demonstrated the presence of an under-compacted soil layer between the steps. At the same time, reducing the step height to less than 350 mm proved impractical, as the strength of the formed soil-cement remained unchanged, which would only increase the overall execution time.

5. Test Procedure and Sample Preparation

The experimental program included physical simulation of the DSM process in laboratory conditions. Soil and cement samples were cast into standard cubic molds with dimensions of 100×100×100 mm. For each combination of soil type, cement content and production method (control and experimental series), a batch of 3 replicates was prepared to ensure statistical reliability. The cast samples were cured under normal humidity conditions (temperature 20±2 °C, relative humidity > 95%) for 28 days. The general view and structural texture of the prepared soil-cement cubic specimens before mechanical testing are shown in Fig. 1.

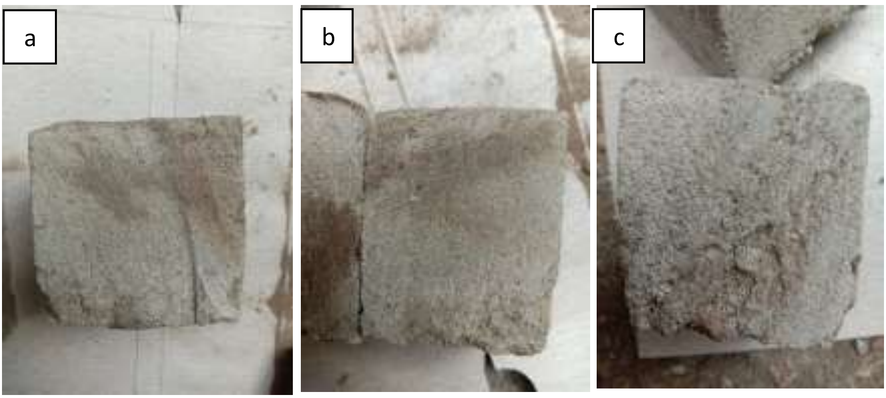

Fig. 1. General view and structural macrotexture of soil-cement specimens (100x100x100 mm): a – clay-cement specimen; b – loam-cement specimen; c – sandy loam-cement specimen

Mechanical tests for unconfined compressive strength were performed using a standard hydraulic testing machine at a constant loading rate of 0.6±0.2 MPa/s. Considering that soil cement with a high binder content (10-20%)

exhibits quasi-brittle behavior similar to low-quality concrete, the test procedure, end surface preparation and statistical processing of the results were performed in accordance with the national standard of Ukraine DSTU B V.2.7-214:2009. The values of the unconfined compressive strength presented in Table 2 are the arithmetic mean of the test results for each series of samples.

Results and discussion

1. Visualization and analysis of the innovative tool kinematics

The fundamental basis for the obtained results is the change in the mechanism of interaction between the drill string and the soil during pile formation. The conceptual diagram of the innovative working tool and the step-wise compaction kinematics, developed based on the patent, is presented in Figure 2.

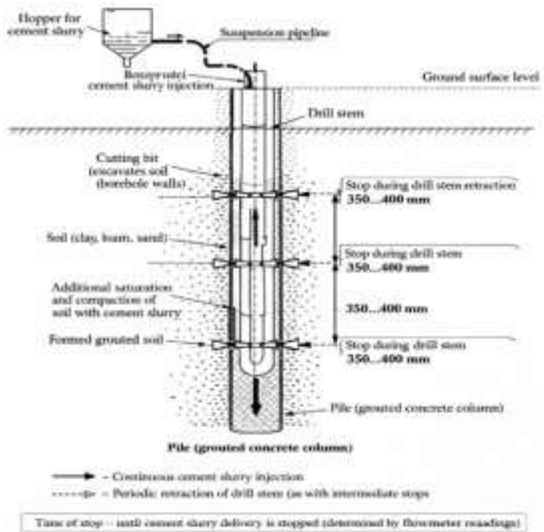

Fig. 2. Conceptual diagram of the innovative drill string and step compaction kinematics

An analysis of Figure 1 allows for a clear tracing of the physics of the proposed process. In the conventional continuous DSM method, which is based solely on the rotation and lifting speeds, the mixing energy is distributed uniformly along the entire length. This is often insufficient for breaking down local soil agglomerates, especially in clayey soils.

In contrast, the proposed step-wise algorithm (with stops every 350...400 mm) transforms the blade kinematics into a cyclic process of local compaction.

Stopping the upward movement of the drill string while continuously injecting the cement slurry creates conditions for mechanical-hydraulic compaction directly within the layer of the soil-cement mixture beneath the cutting blades. This ensures a radical increase in local mixing energy and the forced penetration of the dosed slurry into the pores of the remaining and additionally cut soil. Such a regime allows for the elimination of the primary drawback of DSM-the presence of under-compacted layers-and the formation of a strengthened contact zone between the steps.

2. Quantitative assessment of the strength improvement of soil-cement foundations

The primary criterion for the effectiveness of the proposed technology is the unconfined compressive strength (UCS). The results of experimental studies conducted for three types of soil and three levels of cement dosage (10%, 15%, 20%) are presented in Table 2.

Table 2. Unconfined compressive strength (UCS) for different test series

Soil Type	Cement content (% by soil mass)	UCS (Series 1: Control without compaction), MPa	UCS (Series 2: Experimental with compaction), MPa	Strength increase, %
Clay	10	4,8	6,5	35,4
	15	7,1	9,8	38,0
	20	9,4	12,9	37,2
Loam	10	5,5	7,9	43,6
	15	8,0	11,2	40,0
	20	10,1	14,0	38,6
Sandy loam	10	6,2	9,1	46,8
	15	9,0	12,5	38,9
	20	12,1	15,2	25,6

3. Analysis and discussion of physical and mechanical changes in the structure. A comparative analysis of the data in Table 2 demonstrates a significant positive impact of the optimized kinematics on the soil-cement strength for all investigated soil types and cement dosages. On average, the use of the step-wise compaction method allows for an increase in compressive strength by up to 47% compared to the conventional method.

3.1. Impact on clayey and loamy soils. The highest rates of relative strength increase were recorded for loam (up to 43,6%) and clay (up to 38,0%). This is scientifically explained by the fact that clay particles have a complex porous structure and high cohesion. In conventional DSM, the cement slurry often fails to penetrate deep into the soil agglomerates, creating an «encapsulation effect», where the cement reacts only on the surface of the particles.

Mechanical-hydraulic compaction during the drill string stops destroys these agglomerates, ensuring deeper slurry penetration. Dosed cement injection (for instance, the increase in clay strength with 20% cement from 9,4 to 12,9 MPa) results from pore space optimization and the formation of a denser crystalline lattice. The additional contact time between the slurry and the soil under pressure promotes more complete hydration and the formation of new cementing bonds.

3.2. Impact on sandy loam soils. For sandy loam, which by nature has lower cohesion and higher permeability, the compaction effect is also significant, but the relative increase is lower (up to 46,8% at 10% cement and 25,6% at 20% cement). This is due to the fact that sand particles are less prone to agglomeration.

However, the step-wise method still improves the bearing capacity through a more uniform distribution of cement along the entire length of the pile. The high compressive strength in sandy loam (up to 15,2 MPa at 20% cement) emphasizes that local compaction allows for the maximum utilization of the local soil’s load-bearing potential.

3.3. Substantiation of the optimal compaction step. A vital scientific conclusion is the experimental confirmation of the limit step values (stops every 350...400 mm), as specified in the patent [2]. It was established that stops at a step exceeding 400 mm lead to the formation of local under-compacted soil layers between steps, which significantly reduces the pile’s homogeneity and water resistance. This confirms that the effective radius of local compaction under the cutting blades is limited to this range.

At the same time, reducing the step to less than 350 mm did not lead to a further increase in strength, as the soil matrix was already maximally saturated with the slurry. Such a regime would only unjustifiably increase the execution time and resource consumption. Therefore, the range of 350...400 mm is optimal in terms of the balance between strength and productivity.

4. Assessment of resource-saving potential and environmental feasibility. In modern construction, increasing strength is only one of the goals; cost optimization is equally important. A cost reduction of 25-35% was confirmed through calculation, the results of which are presented in Table 3.

Resource savings of 25-35% (specifically, cement savings of 22.5-30,0% to achieve the same design strength) are a direct result of increased mixing efficiency and homogeneity.

Table 3. Calculated economic efficiency of the step-wise method

Soil Type	Parameter	Conventional DSM Method (Control)	Proposed Step-wise DSM Method (Experiment)	Resource Savings, %
Clay	Design strength, MPa	10	10	-
	Required cement content, %	20	15,5	22,5
Sandy loam	Design strength, MPa	12	12	-
	Required cement content, %	20	14	30,0

Due to local compaction, each unit of cement slurry works more efficiently, creating stronger bonds. This allows for the use of a smaller number of piles on a project or a reduction in pile diameter while maintaining the same bearing capacity. Furthermore, using local soil as the primary aggregate minimizes transportation costs and the environmental footprint compared to constructing piles from pure concrete.

In summary, the results obtained experimentally confirm that the optimization of drill string kinematics through step-wise compaction is an effective, resource-saving, and scientifically substantiated solution for strengthening foundations in weak soils.

Conclusions

The experimental research and physical modeling of optimized drill string kinematics in Deep Soil Mixing (DSM) have demonstrated the high efficiency of the proposed step-wise compaction method. Replacing the conventional continuous tool withdrawal with discrete reverse movement, characterized by regulated stops and dosed cement slurry injection, fundamentally addresses the core challenge of the technology – the structural heterogeneity of the formed soil-cement piles.

In the context of contemporary global research, particularly studies evaluating the impact of mixing parameters on the strength of stabilized soils (e.g., the influence of local mixing energy on unconfined compressive strength), the proposed technology introduces a fundamentally new mechanism for transferring energy to the soil mass. While conventional DSM methods attempt to increase mixing energy through multiple tool passes or varying rotation speeds – which significantly extends operation time without guaranteeing homogeneity – the step-wise algorithm concentrates this energy locally. The mechanical-hydraulic compaction occurring under the expanding blades during stops ensures the targeted and deep penetration of the cement slurry into the soil pores. This avoids the «encapsulation effect» of clay agglomerates and forms a significantly denser contact zone compared to reference continuous mixing methods.

Quantitative results from mechanical testing strongly indicate the effectiveness of this physical process. The proposed method allows for a significant increase (up to 47%) in the compressive strength of the soil-cement compared to samples formed without targeted compaction. This substantial gain in bearing capacity was recorded across all investigated soil types – clay, loam, and sandy loam – with Portland cement dosages ranging from 10% to 20%. Furthermore, the study clearly defined the rational limits of the kinematic parameters: it was experimentally proven that the drill string stop step should be 350...400 mm of the borehole height. Exceeding this height (above 400 mm) inevitably leads to the formation of under-compacted soil layers, compromising the structural integrity, while reducing the step (below 350 mm) yields no further strength increase, making the process technologically redundant.

Beyond purely mechanical advantages, the implementation of controlled local compaction offers a pronounced resource-saving and economic effect. Enhancing the saturation and compaction of the mixture ensures an overall reduction in resource consumption by 25-35%. This is achieved by reducing the required number and length of piles needed to meet the design bearing capacity, as well as by fully utilizing the local excavated soil as the primary construction material. Ultimately, the proposed pile manufacturing method is a reliable innovative solution that comprehensively enhances the water resistance, durability, and bearing capacity of foundations, making step-wise DSM a promising technology for widespread implementation in the construction and reconstruction of facilities in challenging soil conditions.

Conflicts of interest

The authors confirm that they have no conflict of interest regarding the current study, including financial, personal, authorial or any other that could influence the research, as well as the results presented in this article.

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Data availability

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Підвищення міцності ґрунтоцементних паль шляхом оптимізації кінематики бурової штанги при глибинному змішуванні

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Анотація. У цьому дослідженні пропонується вдосконалений метод виготовлення ґрунтоцементних паль з використанням технології глибокого змішування ґрунтів (DSM) для підвищення несучої здатності та довговічності фундаментів у м'яких ґрунтах. Актуальність роботи зумовлена необхідністю підвищення ефективності влаштування основ і фундаментів у складних інженерно-геологічних умовах, де традиційні методи укріплення ґрунтів не завжди забезпечують належні показники міцності та однорідності масиву. У дослідженні представлено концептуальну модель локального ущільнення, яка розглядає свердловину як комбіновану механіко-гідравлічну систему, що дозволяє *точніше описати процес формування ґрунтоцементного елемента та керувати його фізико-механічними властивостями.*

Цей підхід інтегрує безперервне закачування цементного розчину з дискретними зворотними рухами бурильної колони кожні 350-400 мм, що забезпечує інтенсифікацію процесу перемішування та ущільнення ґрунтово-цементної суміші по всій глибині свердловини. Така технологічна схема сприяє формуванню більш щільної та однорідної структури матеріалу, зменшенню пористості та підвищенню адгезійних властивостей між частинками ґрунту та цементного каменю. Лабораторні випробування на глині, суглинку та супіску (вміст цементу 10-20%) підтвердили, що ступінчасте ущільнення збільшує міцність на стиск до 47% (майже у 1,5 рази), досягаючи 12,9 МПа для глини та 15,2 МПа для супіску, що свідчить про високу ефективність запропонованого методу.

Результати досліджень показують, що крок ущільнення, що перевищує 400 мм, призводить до структурної неоднорідності та зниження експлуатаційних характеристик паль, тоді як оптимальний інтервал забезпечує максимальну щільність і рівномірний розподіл напружень у масиві. Додатково встановлено, що контроль параметрів процесу (швидкість підйому інструменту, витрата розчину, кратність реверсних переміщень) має вирішальне значення для досягнення стабільних результатів у польових умовах. Технологія зменшує споживання ресурсів на 25-35% завдяки ефективному використанню місцевих ґрунтів, зниженню витрат цементу та енергії, а також скороченню тривалості виконання робіт.

Запропонований підхід забезпечує ресурсозберігаюче та екологічно доцільне рішення для будівництва фундаментів і підпірних стін у складних геотехнічних умовах, а також має потенціал для широкого впровадження у практику цивільного та промислового будівництва. Отримані результати можуть бути використані при розробці нормативних рекомендацій та вдосконаленні технологічних регламентів виконання робіт із глибокого змішування ґрунтів.

Ключові слова: ґрунтоцементна паля, глибинне змішування ґрунтів (DSM), цементна суспензія, локальне ущільнення, кінематика бурової штанги, несуча здатність