

BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

UDC 624.154:[624.138:666.97]

YU. L. VYNNYKOV¹, O. V. MYKHAILOVSKA²

¹Department “Drilling and Geology”, National university “Yuri Kondratyuk Poltava polytechnic”, Vitaliia Hrytsaienka av., 24, Poltava, Ukraine, 36011, tel. +38 (067) 256 42 86, e-mail: vynnykov@ukr.net, ORCID 0000-0003-2164-9936

²Department “Drilling and Geology”, National university “Yuri Kondratyuk Poltava polytechnic”, Vitaliia Hrytsaienka av., 24, Poltava, Ukraine, 36011, tel. +38 (050) 017 28 17, e-mail: helena_2005@ukr.net, ORCID 0000-0001-7451-3210

MODIFICATIONS OF GEOTECHNICAL CONSTRUCTIVE AND TECHNOLOGICAL SOLUTIONS USING SOIL CEMENT

Purpose. Improvement (modification) of well-known geotechnical structural and technological solutions using soil-cement for specific areas of their rational application. **Methodology.** Current, field-proven trends in geotechnical structural and technological solutions utilizing soil-cement under complex engineering-geological and hydrogeological conditions, as well as within dense urban environments, have been analyzed. The study also examines soil-cement piles, foundations, and special-purpose elements and structures with a wide range of parameters. New technical solutions are compared with the most closely related existing counterparts. This comparative analysis identifies their advantages and disadvantages, essential features shared with the proposed object, the primary objective of the utility model, and the method of its achievement, the technical essence of the utility model, its potential parameters, and the scope of rational application, among others. **Findings.** Utility model patents have been obtained for improved geotechnical structural and technological solutions using soil-cement in the following areas: soil-cement piles for new buildings and structures; foundations and soil masses reinforced with soil-cement elements; industrial and domestic waste disposal sites; walls of protective (fortification) structures in weak soils; and special-purpose structures, etc. **Originality.** The authors have improved geotechnical structural and technological solutions for soil-cement applications within specific areas of their rational use. These enhancements are implemented to increase the load-bearing capacity of piles and enhance the strength of artificial foundations and soil masses composed of soil-cement elements. Furthermore, these solutions aim to reduce the cost and labor intensity associated with constructing artificial foundations for temporary structures and walls of protective (fortification) structures in weak soils. Additional benefits include ensuring high water-impermeability for industrial and domestic waste disposal sites and providing technical support for the implementation of environmental projects. **Practical value.** It is proposed to expand the possibilities and increase the efficiency of using soil cement in geotechnics under difficult engineering geological and hydrogeological conditions.

Keywords: soil-cement pile; soil-cement element; strength; deformability; dense urban areas; complex engineering-geological conditions; deep excavation retaining structure; industrial waste repository, environmental project

Introduction

In geotechnics, soil cement is traditionally understood as a man-made building material created by intensive mixing of natural, and sometimes anthropogenic, sediments with cement binder and water directly at the place of their occurrence. It has been experimentally determined that the mechanical properties of this material depend mainly on: the lithology of dispersed rocks; the pH value of water and the content of water-soluble salts; the proportion of cement in the mixture and its quality; the water-cement ratio and the degree of compaction of the soil-cement mixture; the presence and

percentage of soil-cement reinforcement with steel reinforcement (frame, profiles etc.); the presence of certain additives in the mixture, etc. (Denies, Huybrechts, De Cock, Lameire, Maertens, Vervoort, & Guimond-Barrett, 2015).

The high economic efficiency of employing soil-cement piles, elements, and structures is primarily driven by the minimization of aggregate costs and the feasibility of executing geotechnical projects within dense urban infrastructure. This approach mitigates significant dynamic impacts on surrounding buildings under diverse and challenging engineering-geological conditions. Furthermore, the integration of reinforcing components

and the adjustment of the water-cement ratio enable the achievement of specified strength parameters and ensure structural durability, even when operating in complex hydrogeological environments. However, a critical constraint in the geotechnical application of soil-cement is the susceptibility of its final performance characteristics to the lithological features of the soil mass, including pH levels, concentrations of water-soluble salts, and the presence of organic inclusions within the ground. (Zotsenko, N., Vynnykov, & Zotsenko V., 2015).

To date, empirical correlations regarding the influence of soil-cement mixture components on the mechanical properties of soil-cement piles, elements, and structures have been thoroughly established. Research has also addressed the effects of reinforcement ratios, technological factors, and the temporal factor (curing time) on soil-cement strength.

Furthermore, testing methodologies for soil-cement have been standardized, providing a robust regulatory and normative framework that facilitates the continued implementation of geotechnical structural and technological solutions utilizing soil-cement in engineering practice. (Denies, Bohn, Pandrea, et al., 2024).

The authors have conducted a comprehensive review of the research papers presented at the International Conferences on Soil Mechanics and Geotechnical Engineering (Paris, 2013; Seoul, 2017; Sydney, 2022) and European Conferences on Soil Mechanics and Geotechnical Engineering (Edinburgh, 2015; Lisbon, 2024).

Based on an extensive of successfully implemented projects the following key trends in geotechnical structural and technological solutions using soil-cement have been identified. These researched and field-proven directions include:

- soil-cement piles featuring a wide range of diameters and lengths, reinforced with spatial cages, steel profiles, or pipes. Specific applications include, but are not limited to, piles with diameters starting from 0.6 m and lengths of 6 m and above. (Bzówka, Juzwa, Wanik, & Żyrek, 2015) up to 2.7 m in diameter and up to 36.5 m in length (Armijo Palacio, & Hontoria García, 2015). Design of soil-cement elements in various complex engineering and geological conditions for new buildings and structures;
- soil-cement foundations of spatial configura-

tion in weak soils under seismic conditions (Yamashita, Wakai, & Hamada, 2013);

- reinforced with soil-cement elements (SCE) foundations for new buildings and structures, for example, in sands under seismic conditions (Kudoic, Clayton, & Graaf, 2022), in loess soils and clays capable of swelling (Olinic, E.-D., Manea, Burlacu, & Olinic, 2022), in weak and bulk soils (Kryvosheiev, Farenyuk, Tytarenko, et al., 2017);

- SCE reinforcement of the foundations of existing buildings and structures during their reconstruction (Cristóvão, Nogueira, Hutchinson, Brito, Tomásio, & Pinto, 2015);

- industrial waste storage facilities (Al-Tabbaa, & Harbottle, 2015) and so-called environmental projects (Peter Freitag, Zöhrer, & Reichenauer, 2022);

- retaining (permanent and temporary) structures of deep excavations mainly in conditions of dense urban development (Arcos, Beal, Gil, Dimas, & Segovia, 2024), with a single-row (Boueanu, Ciumeică, Măgureanu, & Sata, 2024) or double-row arrangement of piles (Haugen, Kahlström, Mortensen, Kjærstad, & Pan, 2024), for example, with a depth of 12.6 m for three underground floors of an administrative building in conditions of a historical building (Josifovski, Susinov, & Markov, 2015), in the form of piles (columns) of large (1.7 ... 2.0 m) diameter with a depth of the excavation of 18.3 m (Pulko, & Logar, 2022), using buttresses of retaining walls at a depth of the excavation of 16.0 m (Pohl, Abratis, & Peschken, 2022; Akçakal, Koçak, Velioglu, Sevim, & Kulaç, 2022), “with the caisson effect” at a high groundwater level (Neves, & Pinto, 2015), as well as using the “top-down” building construction technology (Peixoto, & Gomes, 2024) etc.;

- special-purpose structures, such as sluice chambers using piles with a diameter of 1.0 m and a length of 7.5 m in a soil environment aggressive to concrete (Pohl, Abratis, & Peschken, 2022), working chambers of the metro (Chen, Ding, Liu, & Chua, 2015), tunnels under historical development conditions (Ovando-Shelley, Botero-Jaramillo, & Díaz-Guzmán, 2022), as well as for embankments of automobile and railway roads (Tyagi A. & Tyagi P., 2022);

- landslide prevention measures (Deckner, Enbom, Kriege, Borgström, & Forsberg, 2024), including under seismic conditions (Mathieu, Har-

buz, Canecaude, & Storie, 2022) etc.

Consequently, a diverse array of field-proven trends in geotechnical structural and technological solutions utilizing soil-cement has been established. These include soil-cement piles, foundations, and specialized structural elements and facilities characterized by a broad spectrum of performance parameters. Nevertheless, the vast diversity of complex engineering-geological and hydrogeological conditions, necessitates further refinements and modifications of these solutions. Such improvements are essential to optimize their efficiency within specific sectors of rational application.

Purpose

This research is focused on advancing soil-cement geotechnical solutions by modifying their structural design and defining the boundaries for their efficient use.

Methodology

Beyond analyzing current trends in soil-cement geotechnical solutions, this study utilizes a proven inventive methodology to compare new technical designs with established analogues and prototypes. Such an approach enables the determination of technical merits and drawbacks, essential common features, and the core objectives of the utility model, as well as its functional parameters and optimal fields of application.

This research expands the scientific school of soil-cement geotechnical engineering founded by Professor M. Zotsenko at National University “Yuri Kondratyuk Poltava polytechnic”.

Findings

SCE are effectively used for constructing artificial foundations for buildings and structures, as well as artificial massifs for stabilizing landslide-prone areas. Various structural designs can be implemented, such as the soil-cement pile with a variable cross-section (Патент на корисну модель № 157557, 2024). This solution enhances the stability of foundations subjected to significant horizontal loads and secures structures in landslide-prone areas where substantial lateral forces must be resisted.

The design of a soil-cement pile with a variable cross-section consists of a reinforced shaft featuring at least two cylindrical steps, with diameters

decreasing stepwise from top to bottom (Figure 1).

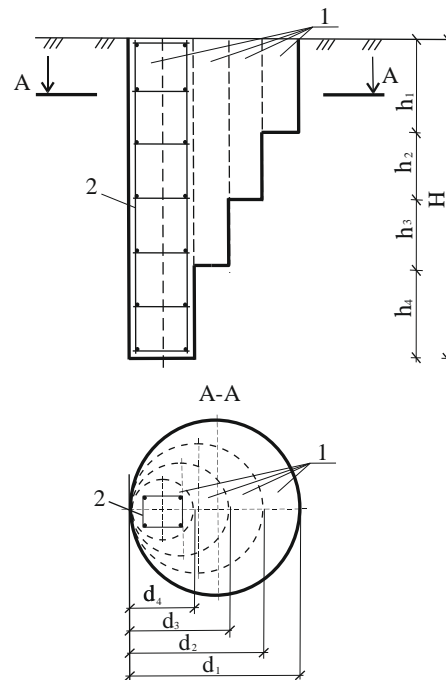


Figure 1. Soil-cement pile of variable cross-section in depth:
1 – cylindrical soil-cement steps;
2 – reinforcing frame

The installation process involves the sequential formation of segments, starting from the upper section, through continuous soil mixing with a working slurry immediately following the completion of the preceding stage. A key structural feature is that the contour of each subsequent lower step remains within the boundaries of the upper one, while their vertical axes may not necessarily coincide. This stepped configuration significantly enhances the pile's bearing capacity, enabling effective resistance to substantial horizontal forces due to the combination of soil resistance along the vertical surfaces of the steps and frictional forces generated at their lower horizontal faces.

The proposed design features a telescopic soil-cement pile comprising four sequential cylindrical segments. The step diameters decrease from 900 mm at the pile head to 300 mm at the base (700 mm and 500 mm for intermediate steps). Structural integrity is provided by a reinforcement cage consisting of four 16-mm diameter longitudinal A-III class steel bars. Depending on the soil conditions, the height of the individual segments (h_1-h_4) is set between 500 and 1000 mm, with a total pile length ranging from 2 to 4 m.

The construction technology for the variable-diameter pile is implemented using deep soil mixing (DSM) equipment. The process originates from the bottom of the excavation, where a blade mixer loosens the soil while simultaneously saturating it with cement slurry to form a homogeneous plastic mass. Initially, the upper tier of the largest diameter d_1 is drilled to the corresponding depth h_1 ; the continuous filling of the borehole with the slurry ensures the stability of the walls, even in weak soil conditions.

A continuous mixing plant prepares the grout, which is then injected under pressure through the hollow-stem drill string swivel via diaphragm or plunger pumps. The pile construction concludes with the immersion of the reinforcement cage into the wet soil-cement column using a vibratory inducer. To ensure proper bonding and ease of penetration, this step must be executed immediately after forming the bottom segment and prior to the onset of the mixture's hardening (setting time).

A continuous mixing plant prepares the grout, which is then injected under pressure through the hollow-stem drill string swivel via diaphragm or plunger pumps. The pile construction concludes with the immersion of the reinforcement cage into the wet soil-cement column using a vibratory inducer. To ensure proper bonding and ease of penetration, this step must be executed immediately after forming the bottom segment and prior to the onset of the mixture's hardening (setting time).

The novelty of this configuration is found in its shift from basic lateral friction to a sophisticated soil-structure interaction mechanism. Essentially, it creates a 'serrated' interlocking effect, where each step provides an additional horizontal bearing surface (or 'lever arm') that contributes to shear resistance. Consequently, the pile achieves enhanced soil engagement by distributing loads across a broader contact surface.

The stability of the structure is enhanced by increasing the resistance of the vertical faces. This stepped configuration utilizes the lateral passive earth pressure against each vertical surface of the steps, which significantly limits the lateral displacement of the structure. The enlarged diameter in the upper section ($d_1=900$ mm) coincides with the zone of maximum bending moment, allowing the reinforcement to operate more efficiently where stresses are highest. Due to the wide upper segments, the pile is securely fixed in the upper

soil layers, which is critical for construction in areas with high groundwater levels or liquid-limit (flowable) clay soils.

Such a configuration makes these piles particularly effective for structures with high windage or those subjected to dynamic lateral loads. It ensures foundation reliability while significantly reducing material consumption compared to massive large-diameter cylindrical piles.

The technology for constructing soil-cement blocks incorporated with fly ash additives has been substantiated (Патент на корисну модель № 157436, 2024). This technology is applicable for the erection of underground structures, block-based retaining walls, and similar constructions. The inclusion of fly ash is intended to enhance the compressive strength of the soil-cement.

The blocks are manufactured in standard dimensions of 250×120×65 mm, enabling their application as versatile structural components across various construction sectors. The fabrication process is based on a slurry prepared in a continuous-flow concrete mixer. This mixture consists of local soils (loam or sandy loam) combined with Grade 400 Portland cement at a dosage of 20 % by weight of the soil, water at a water-cement ratio (W/C) of 1.0, and a reactive fly ash additive. Following intensive mixing for at least 5 minutes, the resulting suspension is cast into molds. The blocks achieve their designed strength through water immersion curing for 28 days at a controlled temperature of 20±2 °C.

The incorporation of fly ash enhances the material microstructure and improves its corrosion resistance, thereby ensuring the effectiveness of these blocks for the construction of load-bearing walls in low-rise buildings and internal partitions. Furthermore, this technology is suitable for retaining walls in landscape engineering, subgrade stabilization, and the installation of building envelopes under complex hydrogeological conditions.

The proposed method is efficient for constructing seepage cutoff walls around hydraulic structures and dams, reinforcing shoulders and embankment slopes for erosion control, and stabilizing excavation floors under challenging hydrogeological conditions. Furthermore, it is applicable for the surface stabilization of fly ash disposal sites and related geo-engineering tasks.

For the construction of artificial foundations for buildings and structures, as well as artificial mas-

sifs intended for the stabilization of landslide-prone areas, the use of soil-cement elements (SCEs) installed via a vibratory method is recommended (Патент на корисну модель № 158388, 2025). The primary feature of this SCE installation process is the transmission of vibrations to the drill bit by means of an integrated internal vibrator during the mixing stages. This approach ensures superior homogenization of the mixture and enhances the structural density of the resulting soil-cement massif.

The following components illustrate an exemplary implementation of the SCE installation method. A DSM rig is positioned at the installation site (Figure 2, *a*), specifically a truck-mounted drilling rig equipped with a power drive. The soil is loosened using a specialized mixing tool, such as a blade-type mixing bit. A water-cement slurry is prepared in a colloidal mixer and injected via a grout pump through a swivel into the drill pipe, ultimately reaching the loosened soil.

The slurry is delivered through a high-pressure hose. The mixture is homogenized throughout the

entire length of the SCE through several downward and upward strokes of the mixing tool (Figure 2, *b*). Vibrational energy is transmitted to the mixing tool by an attached internal vibrator during each mixing cycle or during the final stages of the process (Figure 2, *c*). The estimated vibration amplitude ranges from 0.3 to 0.6 mm, with a frequency of 3000 rpm. The internal vibrator is driven by an electric motor via a flexible shaft.

This approach facilitates the effective compaction of the soil-cement mixture during the installation of SCEs. A significant advantage of this method is the attainment of maximum homogeneity and density within the soil-cement mass directly during the element formation process. Due to intensive dynamic action, the mixture is de-aired and redundant pores are eliminated, which reduces compressibility while simultaneously enhancing the strength characteristics of the finished structures. Consequently, artificial foundations constructed using this method exhibit high load-bearing capacity and minimal deformability.

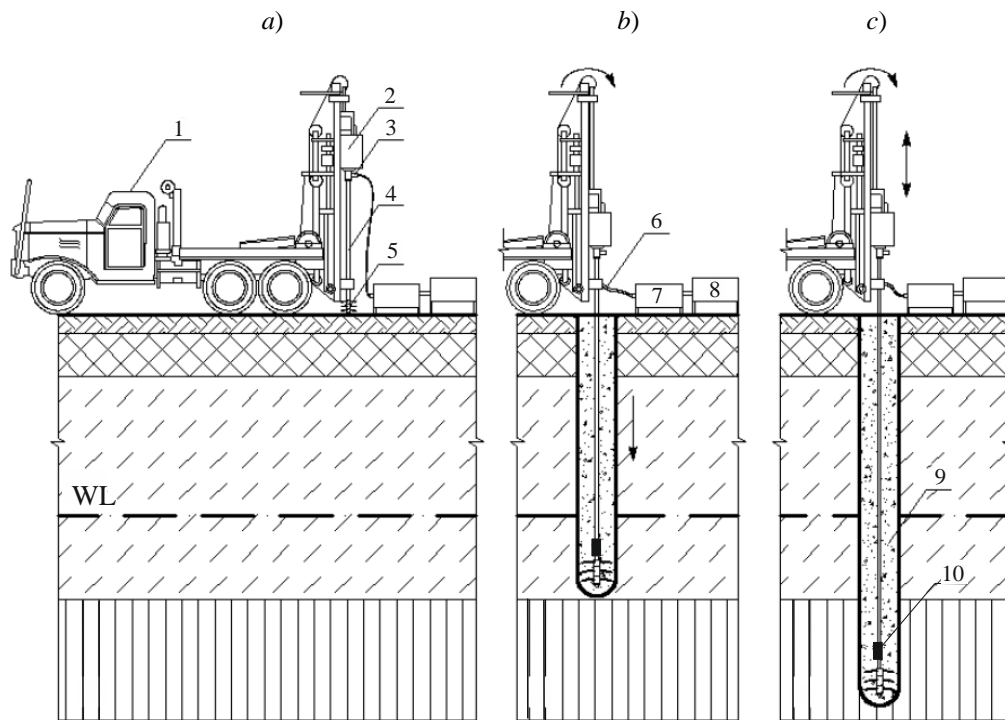


Figure 2. Installation of soil-cement elements:

a) general schematic prior to the installation process;

b) soil loosening process with water-cement slurry (grout) injection;

c) SCE installation with simultaneous vibratory compaction of the mixture;

1 – drilling rig; 2 – power drive; 3 – swivel; 4 – drill pipe; 5 – mixing tool (bit);

6 – high-pressure hose; 7 – grout pump; 8 – colloidal mixer; 9 – SCE; 10 – vibrator

This SCE installation method features a broad range of applications, particularly in weak soil conditions, including: reinforcing the compressible thickness of building and structure foundations to mitigate differential settlement; constructing seepage cutoff walls; stabilizing roadbeds and railway embankments in areas with waterlogged or peaty soils; and enhancing slope stability.

To enhance the structural integrity of SCEs, the installation of soil-cement piles incorporated with fly ash additives has been substantiated (Патент на корисну модель №154729, 2023). During the construction of these SCEs, fly ash derived from the combustion of solid fuels at combined heat and power (CHP) plants is integrated into the mixture.

The technical essence of this solution lies in the application of an optimized binder composition, where the cement slurry is prepared using Grade 400 Portland cement at a dosage of 20 % by total soil weight. The mandatory inclusion of fly ash – a byproduct of solid fuel combustion at CHP – is a key feature of this formulation. Within the framework of DSM technology, the resulting grout is homogenized and delivered through a system of swivels and a drill pipe directly into the SCE installation zone. The use of industrial-grade grout pumps ensures the required degree of uniformity in the stabilization of the soil massif.

Laboratory test results on the 28th day at a temperature of 20 ± 2 °C demonstrated that the incorporation of fly ash into the mixture ensures higher strength of the resulting SCEs compared to the baseline soil-cement composition without additives. The utilization of soil-cement structures with fly ash significantly reduces construction costs through the synergy of local soils and industrial energy waste.

Optimization of the mixture proportions allows for achieving high water-resistance levels up to W12, ensuring reliable protection against moisture seepage. In addition to enhanced compressive strength, this solution contributes to cement savings without compromising the operational parameters of the SCEs. The application of fly ash increases the durability of structures in aggressive environments and supports compliance with environmental safety requirements by recycling industrial byproducts from CHP.

The proposed SCE installation technology is recommended for stabilizing weak foundation soils with minimal cement consumption, as well as for

constructing impermeable barriers around settling ponds, dams, and reservoirs to prevent leachate migration into groundwater.

Soil-cement is particularly effective for artificial foundations of structures, especially temporary ones, in flooded or waterlogged areas composed of weak soils (Патент на корисну модель № 161924, 2025). Specifically, a foundation design is proposed in which the SCEs are integrated with reinforced concrete slabs to ensure collaborative structural performance (Figure 3).

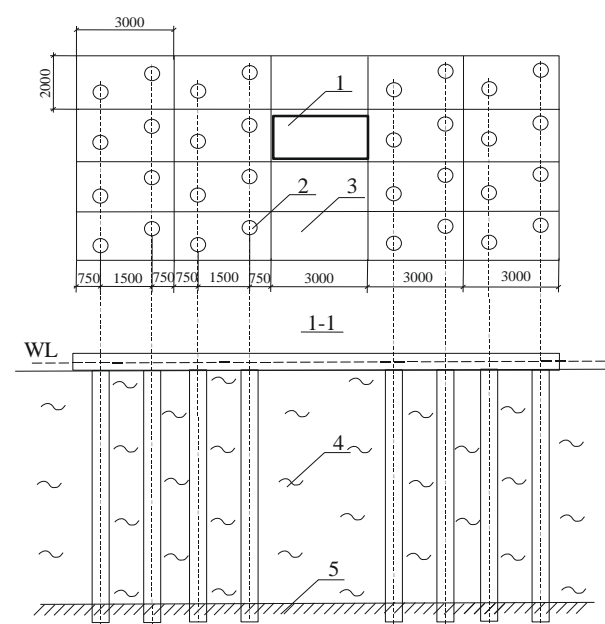


Figure 3. Method for constructing a foundation on an artificial base:

- 1 – service hole (e.g., for drilling rig equipment);
- 2 – service holes for SCE installation;
- 3 – reinforced concrete pavement slabs; 4 – soft soil massif;
- 5 – underlying low-compressibility soil layer

The technological cycle commences with the placement of precast reinforced concrete slabs, measuring 3×2 m, onto the prepared site surface. These slabs are pre-manufactured with service holes 300 mm in diameter. The primary load-bearing capacity of the system is derived from the SCEs, which are installed directly through these apertures in the slabs. The embedment depth of the SCEs depends on the thickness of the weak soil layers; typically, the base of the SCE should be anchored into an underlying low-compressibility soil layer. The final stage involves the structural interlocking of the slabs to transform them into a rigid platform. This method ensures effective load distribution across the foundation and maintains the structural stability of the facility under chal-

lenging hydrogeological conditions.

The primary advantage of this method lies in eliminating the need for a load-distribution (crushed stone) cushion or dewatering measures when constructing SCE-based foundations in flooded or waterlogged areas composed of weak soils. Furthermore, upon the decommissioning of temporary structures, all precast foundation components can be rapidly and completely dismantled for reuse. Following minimal reclamation efforts, the site can be restored to its original agricultural use.

Due to the high water resistance and chemical stability of SCEs, a technical solution for constructing waste containment facilities has been substantiated (Патент на корисну модель № 140153, 2019). These facilities are erected to minimize environmental risks by preventing the leakage of hazardous substances into the ecosystem. The proposed solution involves a closed-type storage system, the key element of which is a monolithic vertical barrier constructed using the “slurry wall” principle.

The SCEs are formed with diameters ranging

from 0.3 to 0.8 m and depths of up to 30 m. To guarantee absolute structural integrity and impermeability, adjacent SCEs are installed with overlapping cross-sections; specifically, the center-to-center spacing is set at $0.8d$ (where d is the element diameter). Furthermore, the barrier is embedded into impermeable strata to a minimum depth of 1 m. Following the hydration and hardening phases of the soil-cement, the internal soil core is excavated (comprising up to 60 % of the total volume). The direct filling of the reservoir with drilling and operation waste from oil and gas wells commences only after the material achieves its design strength, noting that the structure’s water resistance parameters continue to improve over time.

The schematic of the containment facility is presented in Figure 4. The geometry, capacity, and embedment depth are determined specifically for each location during the development of working documentation. The design phase involves a comprehensive analysis of the rock type and category, groundwater levels, and the positioning of impermeable strata.

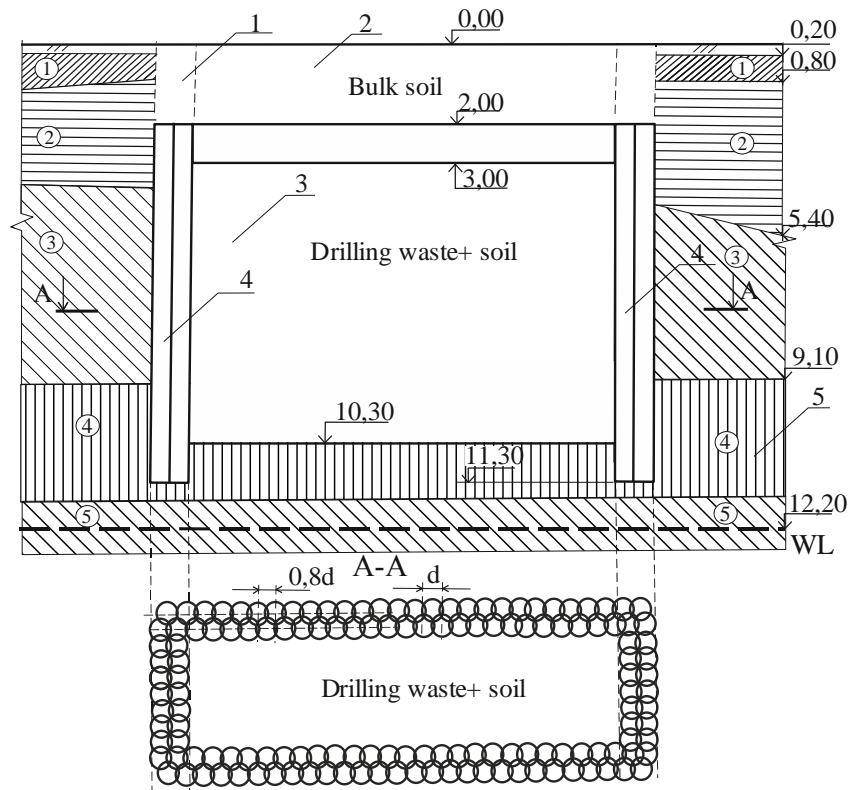


Figure 4. Permanent storage facility:
 1 – SCE; 2 – soil-cement capping layer; 3 – drilling mud;
 4 – impermeable cutoff wall (slurry wall) constructed from SCEs; 5 – impermeable soil layer

Such structures are effectively utilized as sludge pits or hazardous waste repositories. When capped with a soil-cement layer placed over sludge thickened to a stiff-plastic consistency (achieved by mixing local soil with drilling mud), the facility offers several advantages: low construction costs due to the utilization of an in-situ impermeable soil layer as the reservoir bottom; high water resistance (W12); significant compressive strength (2 MPa); and enhanced environmental safety and durability. Due to the high water resistance and chemical stability of soil-cement, a septic tank design featuring walls constructed from soil-cement elements (SCEs) has been developed (Патент на корисну модель № 158939, 2025).

This development relates to engineering systems designed for the collection, accumulation, and primary filtration of domestic wastewater. It is specifically oriented toward decentralized sewerage conditions, such as servicing private house-

holds, dacha communities, cottage settlements, and temporary facilities lacking access to centralized sewage networks. The technical essence of this solution lies in the fact that the vertical walls of the septic tank are manufactured as seamless structures using an impermeable material (soil-cement).

The dimensions of the SCEs, the embedment depth of their base below the septic tank floor, and the overall configuration of the unit are determined based on site-specific conditions, taking into account soil category, groundwater levels, and related geotechnical factors. It is recommended to position the septic tank floor within an impermeable soil stratum (such as clay or heavy silty loam). Alternatively, a soil-cement or concrete bedding with waterproofing layers should be installed to prevent the infiltration of wastewater into the underlying soil mass. The diameter of the SCEs typically ranges from $d=200$ to 500 mm, with a configuration consisting of one or two rows (Figure 5).

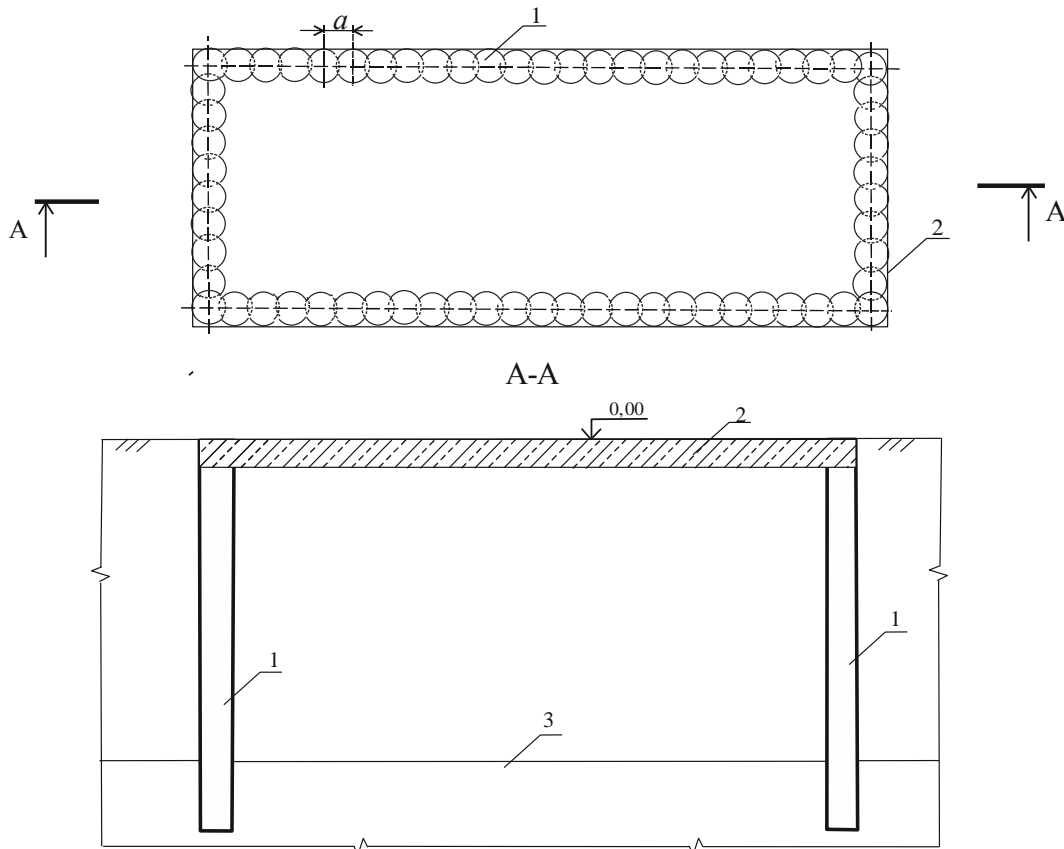


Figure 5. Plan view of the domestic wastewater storage septic tank

A key advantage of this septic tank design, particularly in areas with high groundwater tables, is its exceptional sealing performance. The creation of a continuous vertical barrier anchored into im-

permeable strata effectively eliminates the filtration of toxic substances or wastewater into aquifers and surrounding soils. The technology utilizes local soil as the primary aggregate for SCE produc-

tion, thereby minimizing the logistical costs associated with delivering construction materials such as crushed stone and sand. Furthermore, the strength and water resistance of the soil-cement exhibit a steady increase over time, ensuring the long-term durability of the structures.

The design of fortification structures utilizing SCEs has been substantiated (Патент на корисну модель № 139326, 2019). This method involves the installation of a dense SCE-based screen along the walls of the fortification, which requires reinforcement to ensure sufficient stability against caving or collapse under dynamic impact (Figure 6).

The reinforcement of the building envelopes for such facilities using soil-cement technology is realized through a sequential series of engineering stages. Initially, the geotechnical properties of the site's soil are analyzed to evaluate the foundation parameters. The feasibility of applying soil-cement is dictated by hydrogeological conditions: if the soils exhibit sufficient density and the groundwater table is recorded significantly below the floor elevation of the projected structure, the method may be economically inefficient. In other scenarios, reinforcing the walls of the structures serves as a rational measure to ensure their overall stability.

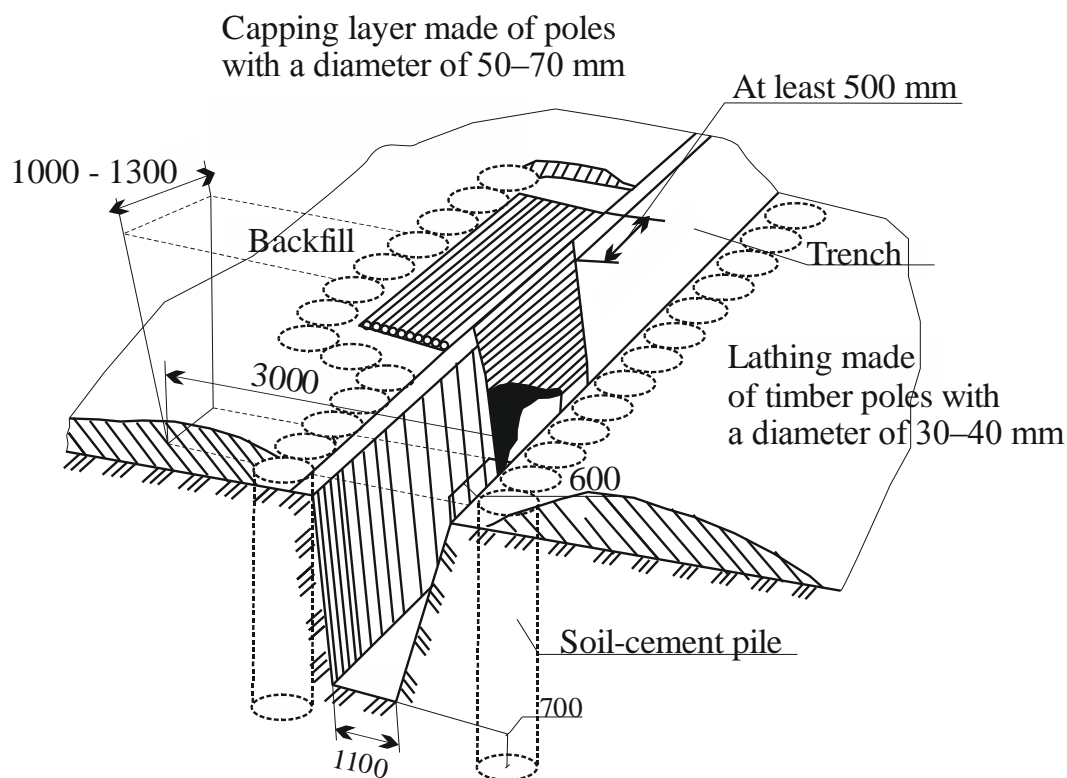


Figure 6. Soil-cement protective structure

The formation of protective elements is executed using DSM technology. The parameters of the SCEs are determined by the soil type and the depth of the aquifers. The construction cycle commences with the removal and stockpiling of the fertile topsoil layer. Following the formation of the soil-cement perimeter, the internal soil volume is excavated, which may subsequently be utilized as a component of the working mixture. To protect the excavation from surface runoff and meltwater, a safety earthen berm 0.5 m in height is constructed along the perimeter, while a system of sumps and

drainage channels is implemented for precipitation management.

To create a continuous impermeable screen, the SCEs are positioned flush with each other. For instance, with an SCE cross-section of 0.3 m, the center-to-center spacing between adjacent elements is set at 0.2 m. To ensure reliable anchoring of the lower section of the structure, the protective barrier is embedded 0.5 ... 0.7 m below the design elevation of its floor. The primary advantages of soil-cement reinforcement include low production costs due to the utilization of in-situ soil and high com-

pressive strength.

An anaerobic bioreactor (digester) has been developed for biogas production through the anaerobic decomposition of biological waste, including fallen leaves from trees and shrubs, as well as plant residues. This system is suitable for implementation at both industrial enterprises and private households (Патент на корисну модель № 145004, 2020).

The application of DSM technology to create the monolithic body of the anaerobic bioreactor results in an integrated, hermetically sealed structure made of modified soil-cement. The fabrication of cylindrical elements directly within the soil massif significantly enhances the operational reliability and durability of the system designed for the generation of biogas and organic fertilizers.

To form a reliable protective screen and ensure the stability of the structure's walls, the soil-cement columns are positioned flush with one another, following the principle of a continuous curtain wall. The technological scheme involves the overlapping of adjacent elements (similar to the previous example). This configuration enables the creation of an impermeable barrier that guarantees the geometric stability of the bioreactor and the absolute airtightness of its working volume. Constructing the housing as a single, monolithic structure without prefabricated joints minimizes the risks of biogas leakage or the filtration of aggressive effluents into the environment.

Since the primary structural component is in-situ soil, the volume of imported materials (such as sand and crushed stone) is reduced by 70 ... 80%. The technology aligns with the principles of sustainable construction by maximizing the utilization of the site's natural resources and minimizing the anthropogenic impact on the soil, as there is no need to excavate and transport surplus spoil. The creation of a "slurry wall" provides reliable resistance to soil and groundwater pressure, enabling the construction of deep reactors even in unstable or waterlogged geological conditions.

Originality and practical value

The geotechnical structural and technological solutions for soil-cement applications have been enhanced within specific areas of their rational utilization.

Specifically, advancements have been achieved in: increasing the load-bearing capacity of piles, as

well as the strength of artificial foundations and soil-cement massifs; reducing the cost and labor intensity of constructing soil-cement foundations for temporary structures and protective (fortification) walls in weak soils; ensuring high impermeability for industrial and domestic waste containment facilities; facilitating the implementation of environmental engineering projects.

The practical value of this research lies in expanding the operational capabilities and enhancing the efficiency of soil-cement applications within the field of geotechnics. This is particularly relevant for projects executed under challenging engineering-geological and hydrogeological conditions, where traditional construction methods may be technically constrained or economically unfeasible.

Conclusions

In conclusion, the author's modifications to established structural and technological solutions enhance the efficiency and expand the functional capabilities of soil-cement applications in Geotechnics, specifically through:

- Variable-section soil-cement piles: These elements, characterized by cross-sections that vary with depth, provide significantly higher load-bearing capacity under lateral (horizontal) loads;
- Ash-modified soil-cement blocks: The incorporation of fly ash increases structural strength while simultaneously reducing cement consumption, ensuring environmental safety and long-term durability;
- Vibratory compaction of soil-cement mixtures: The implementation of vibro-compaction during the installation of SCEs allows for high-quality densification of the mixture. This results in high-density elements with low compressibility and superior strength. Consequently, artificial foundations or massifs created using these SCEs for stabilizing landslide-prone areas exhibit minimal deformability and enhanced structural stability (load-bearing capacity).
- Advantages of ash-modified SCEs: Low production costs due to the utilization of in-situ soil and industrial waste; high water resistance (W12); increased compressive strength; cement savings; environmental safety, and long-term durability.
- Advantages of artificial foundation systems: The method eliminates the need for crushed stone cushions or dewatering during the construc-

tion of vertical SCE-based foundations in flooded or waterlogged areas composed of weak soils. Furthermore, after decommissioning temporary structures (such as drilling rigs for oil and gas wells), all prefabricated foundation elements can be quickly and completely dismantled for reuse; with minimal reclamation efforts, the site can be restored to its original agricultural use.

- Permanent sludge storage for toxic waste: This method reliably prevents the infiltration of toxic drilling and production waste from oil and gas wells into the underlying soil.

- Domestic wastewater storage septic tank: Provides a reliable seal against wastewater filtration into the surrounding soil massif while simultaneously reducing construction costs and labor intensity.

- Wall reinforcement for protective (fortification) structures: The advantages of using SCEs in weak soils include low cost, high compressive strength (2 MPa), environmental safety, and durability.

- Bioreactor housing for biogas production: This construction method ensures the structural stability of the unit's walls under any engineering-geological conditions.

REFERENCES

- Akçakal, Ö., Koçak, B., Velioğlu, N., Sevim, O., & Kulaç, H. F. (2022). Decision process for selection of the toe improvement pattern in retaining structures - Case studies. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering*, 2, Sydney, Australian Geomechanics Society, 4111-4114.
- Al-Tabbaa, A., & Harbottle, M. J. (2015). Self-healing materials and structures for geotechnical and geo-environmental applications. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development*, Edinburgh, 589-594.
- Arcos, J. L., Beal, X., Gil, R., Dimas, J. M., & Segovia, M. (2024). Design and execution of retaining-walls using the reinforced jet-grouting technique. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 2071-2075. DOI: <https://doi.org/10.1201/9781003431749-390>
- Armijo Palacio, G., & Hontoria García, E. (2015). Jet grouting column diameter in terms of the drilling and grouting specific energies. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development*, Edinburgh, 2, 1023-1028.
- Boureau, A., Ciumeică, D., Măgureanu, A., & Sata, L. (2024). Secant piles pit enclosure made with deep soil mixing columns and CFA piles. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 2113-2116. DOI: <https://doi.org/10.1201/9781003431749-399>
- Bzówka, J., Juzwa, A., Wanik, L. & Żyrek, T. (2015). Analysis of trial loading tests results of jet grouting columns. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development*, Edinburgh, 2, 1103-1108.
- Chen, E. J., Ding, L. Y., Liu, Y. & Chua, T. S. (2015). Uncertainties of construction quality in soil-cement reinforcement at metro TBM work shaft. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development*, Edinburgh, 2, 3481-3486.
- Cristóvão, A., Nogueira, A., Hutchinson, R., Brito, D., Tomásio, R., & Pinto, A. (2015). Jet grouting columns operating as reaction platform for building uplift and soil liquefaction mitigation – Christchurch Art Gallery, New Zealand. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development*, Edinburgh, 2, 1071-1077.
- Deckner, F., Enbom, V., Kriege, A., Borgström, K., & Forsberg, T. (2024). Monitoring of soil deformations induced by deep mixing using an FME-based data analysis tool. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 1555-1559. DOI: <https://doi.org/10.1201/9781003431749-288>
- Denies, N., Bohn, C., Pandrea, P., et al. (2024). Eurocode 7 – Second generation. Design of ground improvement works. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 1566-1571. DOI: <https://doi.org/10.1201/9781003431749-290>
- Denies, N., Huybrechts, N., et al. (2015). Thoughts on the durability of the soil mix material. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development*, Edinburgh, 2, 1403-1408.
- Haugen, M. K., Kahlström, M., Mortensen, P. A., Kjærstad, K. M., & Pan, Y. (2024). Consequences of geometrical imperfections for deep dry mixing columns in a deep excavation pit. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 2323-2326. DOI: <https://doi.org/10.1201/9781003431749-444>
- Josifovski, J., Susinov, B. & Markov, I. (2015). Analysis of soldier pile wall with jet-grouting as retaining system for deep excavation. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development*, Edinburgh, 3953-3958.

- Kryvosheiev, P., Farenjuk, G., Tytarenko, V., et al. (2017). Innovative projects in difficult soil conditions using artificial foundation and base, arranged without soil excavation. In: *Proc. of 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, Seoul*, 3007-3010.
- Kudoic, K., Clayton, P., & Graaf, K. (2022). A trial of soil mixing options for a lattice cell ground improvement design in Holocene sandy soils containing pumice. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 2839-2844.
- Neves, M., & Pinto, A. (2015). The use of CSM technology in permanent or temporary retaining structures with a cofferdam effect. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development, Edinburgh, 2*, 631-636.
- Mathieu, F., Harbuz, H., Canecaude, M., & Storie, L. (2022). Jet grout column construction and quality controls for seismic strengthening Auckland's waterfront. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 2985-2989.
- Olinic, E.-D., Manea, S., Burlacu, C.-A., & Olinic, T. (2022). A methodology for evaluating the level of improvement of the soils by physical and chemical mixing and its application in several projects in Romania. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 3037-3042.
- Ovando-Shelley, E., Botero-Jaramillo, E., & Díaz-Guzmán, M. A. (2022). Jet Grouting to mitigate damage induced by tunneling near the church of San Francisco de Asis in Guadalajara, Mexico. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 4441-4444.
- Peixoto, A., & Gomes, P. (2024). Application of Cutter Soil Mixing technology in retaining walls. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 2528-2533.
- Peter Freitag, P., Zöhrer, A. & Reichenauer, T. G. (2022). In situ chemical oxidation/reduction using the jet grouting technique (HaloCrete®). In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 3763-3767.
- Pohl, M., Abratis, J., & Peschken, G. (2022). Jet grouted tieback piles at high loads in an aggressive soil environment. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 4157-4162.
- Pulko, B., & Logar, J. (2022). Numerical assessment of jet-grouting columns for deep excavation support. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 917-920.
- Tyagi, A., & Tyagi, P. (2022). Failure behaviour of deep cement mixed columns under embankment loading. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 3131-3136.
- Yamashita, K., Wakai, S., & Hamada, J. (2013). Large-scale Piled Raft with Grid-Form Deep Mixing Walls on Soft Ground. In: *Proc. of the 18th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, Paris*. 2637-2640.
- Zotsenko, N., Vynnykov, Yu., & Zotsenko, V. (2015). Soil-cement piles by boring-mixing technology. In *Energy, energy saving and rational nature use. Oradea University Press*, 192-253.
- Патент на корисну модель № 139326 (2019). *Спосіб закріплення стінок захисних споруд із застосуванням ґрунтоцементних елементів*. Зоценко М. Л., Михайловська О. В. Номер заявки u201907274, 26.12.2019. Бюл. № 1.
- Патент на корисну модель № 140153 (2019). *Спосіб влаштування довічного шламосховища для токсичних відходів*. Зоценко М. Л., Михайловська О. В. Номер заявки u201907230, 10.02.2020. Бюл. № 3.
- Патент на корисну модель № 145004 (2020). *Спосіб влаштування корпусу біореактора для виробництва біогазу*. Клименко В. В., Зоценко М. Л., Михайловська О. В. Номер заявки u202003742, 11.11.2020. Бюл. № 21.
- Патент на корисну модель № 154729 (2023). *Спосіб влаштування ґрунтоцементних елементів з добавкою золи*. Зоценко М. Л., Михайловська О. В. Номер заявки u202301242, 14.12.2023 Бюл. № 50.
- Патент на корисну модель № 157436 (2024). *Спосіб влаштування ґрунтоцементних блоків з добавкою золи*. Михайловська О. В. Номер заявки u202401222, 17.10.2024. Бюл. № 42.
- Патент на корисну модель № 157557 (2024). *Ґрунтоцементна паля змінного перерізу за глибиною*. Винников Ю. Л., Михайловська О. В. Номер заявки u 2024 02127, 31.10.2024. Бюл. № 44.
- Патент на корисну модель № 158388 (2025). *Спосіб влаштування ґрунтоцементних елементів*. Винников Ю.Л., Михайловська О. В. Номер заявки u 2024 03239, 29.01.2025, Бюл. № 5.
- Патент на корисну модель № 158939 (2025). *Накопичувальний септик побутових стічних вод*. Винников Ю. Л., Михайловська О. В. Номер заявки u 2024 04618, 09.04.2025, Бюл. № 15.
- Патент на корисну модель № 161924 (2025). *Спосіб влаштування фундаменту на штучній основі*. Винников Ю. Л., Михайловська О. В. Номер заявки u 2025 00287, 21.01.2026, Бюл. № 3.

Ю. Л. ВИННИКОВ¹, О. В. МИХАЙЛОВСЬКА²

¹Кафедра «Буріння та геології», Національний університет «Полтавська політехніка імені Юрія Кондратюка», пр. Віталія Грицаєнка, 24, Полтава, Україна, 36011, тел. +38 (067) 256 42 86, ел. пошта vynnykov@ukr.net, ORCID 0000-0003-2164-9936

²Кафедра «Буріння та геології», Національний університет «Полтавська політехніка імені Юрія Кондратюка», пр. Віталія Грицаєнка, 24, Полтава, Україна, 36011, тел. +38 (050) 017 28 17, ел. пошта helena_2005@ukr.net, ORCID 0000-0001-7451-3210

МОДИФІКАЦІЇ ГЕОТЕХНІЧНИХ КОНСТРУКТИВНО-ТЕХНОЛОГІЧНИХ РІШЕНЬ ІЗ ВИКОРИСТАННЯМ ҐРУНТОЦЕМЕНТУ

Мета. Удосконалення (модифікація) відомих геотехнічних конструктивно-технологічних рішень із використанням ґрунтоцементу для певних областей їх раціонального використання. **Методика.** Проаналізовано сучасні вже апробовані напрямки у геотехнічних конструктивно-технологічних рішеннях з використанням ґрунтоцементу у складних інженерно-геологічних і гідрогеологічних умовах, а також за умов щільної міської забудови, зокрема ґрунтоцементні палі, фундаменти, елементи та споруди спеціального призначення зі значним діапазоном параметрів. Нові технічні рішення порівнюються з найбільш близькими технічними рішеннями. При цьому виявляються їх переваги та недоліки, суттєві ознаки, загальні з об'єктом, що заявляється, завдання, покладене в основу корисної моделі, спосіб його вирішення, суть корисної моделі, її можливі параметри, область раціонального використання і т. ін. **Результати.** Отримано патенти на корисну модель, в яких удосконалені геотехнічні конструктивно-технологічні рішення із використанням ґрунтоцементу за наступними напрямками: ґрунтоцементні палі під нові будівлі та споруди; армовані ґрунтоцементними елементами основи та ґрунтові масиви; сховища промислових і побутових відходів; стінки захисних (фортифікаційних) споруд у слабких ґрунтах; споруди спеціального призначення і т. ін. **Наукова новизна.** Удосконалено геотехнічні конструктивно-технологічні рішення при застосуванні ґрунтоцементу у певних областях їх раціонального використання, зокрема для: підвищення несучої здатності палей, а також міцності штучних основ і масивів з ґрунтоцементних елементів; зниження вартості та трудомісткості зведення штучних основ з ґрунтоцементних елементів тимчасових споруд і стінок захисних (фортифікаційних) споруд у слабких ґрунтах; високої водонепроникності сховищ промислових і побутових відходів; реалізації екологічних проєктів. **Практична значимість.** Розширення можливостей і підвищення ефективності використання ґрунтоцементу в геотехніці за складних інженерно-геологічних і гідрогеологічних умов.

Ключові слова: ґрунтоцементна паля; ґрунтоцементний елемент; щільна міська забудова; складні інженерно-геологічні умови; утримуюча конструкція глибокого котловану; сховище промислових відходів; екологічний проєкт

REFERENCES

- Akçakal, Ö., Koçak, B., Velioglu, N., Sevim, O., & Kulaç, H. F. (2022). Decision process for selection of the toe improvement pattern in retaining structures - Case studies. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 4111-4114. (in English)
- Al-Tabbaa, A., & Harbottle, M. J. (2015). Self-healing materials and structures for geotechnical and geo-environmental applications. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development, Edinburgh*, 589-594. (in English)
- Arcos, J. L., Beal, X., Gil, R., Dimas, J. M., & Segovia, M. (2024). Design and execution of retaining-walls using the reinforced jet-grouting technique. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal, 2071-2075*. DOI: <https://doi.org/10.1201/9781003431749-390> (in English)
- Armijo Palacio, G., & Hontoria García, E. (2015). Jet grouting column diameter in terms of the drilling and grouting specific energies. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development, Edinburgh, 2, 1023-1028*. (in English)
- Boureanu, A., Ciumeică, D., Măgureanu, A., & Sata, L (2024). Secant piles pit enclosure made with deep soil mixing columns and CFA piles. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal, 2113-2116*. DOI: <https://doi.org/10.1201/9781003431749-399> (in English)
- Bzówka, J., Juzwa, A., Wanik, L. & Żyrek, T. (2015). Analysis of trial loading tests results of jet grouting columns.

In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development, Edinburgh, 2*, 1103-1108. (in English)

Chen, E. J., Ding, L. Y., Liu, Y. & Chua, T. S. (2015). Uncertainties of construction quality in soil-cement reinforcement at metro TBM work shaft. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development, Edinburgh, 2*, 3481-3486. (in English)

Cristóvão, A., Nogueira, A., Hutchinson, R., Brito, D., Tomásio, R., & Pinto, A. (2015). Jet grouting columns operating as reaction platform for building uplift and soil liquefaction mitigation – Christchurch Art Gallery, New Zealand. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development, Edinburgh, 2*, 1071-1077. (in English)

Deckner, F., Enbom, V., Kriege, A., Borgström, K., & Forsberg, T. (2024). Monitoring of soil deformations induced by deep mixing using an FME-based data analysis tool. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 1555-1559. DOI: <https://doi.org/10.1201/9781003431749-288> (in English)

Denies, N., Bohn, C., Pandrea, P., et al. (2024). Eurocode 7 – Second generation. Design of ground improvement works. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 1566-1571. DOI: <https://doi.org/10.1201/9781003431749-290> (in English)

Denies, N., Huybrechts, N., et al. (2015). Thoughts on the durability of the soil mix material. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development, Edinburgh, 2*, 1403-1408. (in English)

Haugen, M. K., Kahlström, M., Mortensen, P. A., Kjærstad, K. M., & Pan, Y. (2024). Consequences of geometrical imperfections for deep dry mixing columns in a deep excavation pit. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 2323-2326. DOI: <https://doi.org/10.1201/9781003431749-444> (in English)

Josifovski, J., Susinov, B. & Markov, I. (2015). Analysis of soldier pile wall with jet-grouting as retaining system for deep excavation. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development, Edinburgh*, 3953-3958. (in English)

Kryvosheiev, P., Farenjuk, G., Tytarenko, V., et al. (2017). Innovative projects in difficult soil conditions using artificial foundation and base, arranged without soil excavation. In: *Proc. of 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, Seoul*, 3007-3010. (in English)

Kudoic, K., Clayton, P., & Graaf, K. (2022). A trial of soil mixing options for a lattice cell ground improvement design in Holocene sandy soils containing pumice. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 2839-2844. (in English)

Neves, M., & Pinto, A. (2015). The use of CSM technology in permanent or temporary retaining structures with a cofferdam effect. In: *Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering for Infrastructure and Development, Edinburgh, 2*, 631-636. (in English)

Mathieu, F., Harbuz, H., Canecaude, M., & Storie, L. (2022). Jet grout column construction and quality controls for seismic strengthening Auckland's waterfront. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 2985-2989. (in English)

Olinic, E.-D., Manea, S., Burlacu, C.-A., & Olinic, T. (2022). A methodology for evaluating the level of improvement of the soils by physical and chemical mixing and its application in several projects in Romania. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 3037-3042. (in English)

Ovando-Shelley, E., Botero-Jaramillo, E., & Díaz-Guzmán, M. A. (2022). Jet Grouting to mitigate damage induced by tunneling near the church of San Francisco de Asis in Guadalajara, Mexico. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 4441-4444. (in English)

Peixoto, A., & Gomes, P. (2024). Application of Cutter Soil Mixing technology in retaining walls. In: *Proc. of the XVIII ECSMGE, Nuno Guerra, Lisbon, Portugal*, 2528-2533. (in English)

Peter Freitag, P., Zöhrer, A. & Reichenauer, T. G. (2022). In situ chemical oxidation/reduction using the jet grouting technique (HaloCrete®). In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 3763-3767. (in English)

Pohl, M., Abratis, J., & Peschken, G. (2022). Jet grouted tieback piles at high loads in an aggressive soil environment. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 4157-4162. (in English)

Pulko, B., & Logar, J. (2022). Numerical assessment of jet-grouting columns for deep excavation support. In: *Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society*, 917-920. (in English)

Tyagi, A., & Tyagi, P. (2022). Failure behaviour of deep cement mixed columns under embankment loading. In:

Proc. of the 20th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, 2, Sydney, Australian Geomechanics Society, 3131-3136. (in English)

Yamashita, K., Wakai, S., & Hamada, J. (2013). Large-scale Piled Raft with Grid-Form Deep Mixing Walls on Soft Ground. In: *Proc. of the 18th Intern. Conf. on Soil Mechanics and Geotechnical Engineering, Paris. 2637-2640. (in English)*

Zotsenko, N., Vynnykov, Yu., & Zotsenko, V. (2015). Soil-cement piles by boring-mixing technology. In *Energy, energy saving and rational nature use. Oradea University Press, 192-253. (in English)*

Patent na korysnu model № 139326 (2019). *Sposib zakriplennia stinok zakhysnykh sporud iz zastosuvanniam gruntotsementnykh elementiv.* Zotsenko M. L., Mykhailovska O. V. Nomer zaiavky u201907274, 26.12.2019. Biul. № 1. (in Ukrainian)

Patent na korysnu model № 140153 (2019). *Sposib vlashtuvannia dovichnoho shlamoskhovyshcha dlia toksychnykh vidkhodiv.* Zotsenko M. L., Mykhailovska O. V. Nomer zaiavky u201907230, 10.02.2020. Biul. № 3. (in Ukrainian)

Patent na korysnu model № 145004 (2020). *Sposib vlashtuvannia korpusu bioreaktora dlia vyrobnytstva biohazu.* Klymenko V. V., Zotsenko M. L., Mykhailovska O. V. Nomer zaiavky u202003742, 11.11.2020. Biul. № 21. (in Ukrainian)

Patent na korysnu model № 154729 (2023). *Sposib vlashtuvannia gruntotsementnykh elementiv z dobavkoiu zoly.* Zotsenko M. L., Mykhailovska O. V. Nomer zaiavky u202301242, 14.12.2023 Biul. № 50. (in Ukrainian)

Patent na korysnu model № 157436 (2024). *Sposib vlashtuvannia gruntotsementnykh blokiv z dobavkoiu zoly.* Mykhailovska O. V. Nomer zaiavky u202401222, 17.10.2024. Biul. № 42. (in Ukrainian)

Patent na korysnu model № 157557 (2024). *Gruntotsementna palia zminnoho pererizu za hlybynoi.* Vynnykov Yu. L., Mykhailovska O. V. Nomer zaiavky u 2024 02127, 31.10.2024. Biul. № 44. (in Ukrainian)

Patent na korysnu model № 158388 (2025). *Sposib ulashtuvannia gruntotsementnykh elementiv.* Vynnykov Yu. L., Mykhailovska O.V. Nomer zaiavky u 2024 03239, 29.01.2025, Biul. № 5. (in Ukrainian)

Patent na korysnu model № 158939 (2025). *Nakopychuvalni septyk pobutovykh stichnykh vod.* Vynnykov Yu. L., Mykhailovska O. V. Nomer zaiavky u 2024 04618, 09.04.2025, Biul. № 15. (in Ukrainian)

Patent na korysnu model № 161924 (2025). *Sposib ulashtuvannia fundamentu na shtuchnii osnovi.* Vynnykov Yu. L., Mykhailovska O. V. Nomer zaiavky u 2025 00287, 21.01.2026, Biul. № 3. (in Ukrainian)

Article received: 29.12.2025.

Review date: 02.03.2026.

Publication date: 29.05.2026.