CETRA^{2026} 27-30 May 2026, Bol, Island Brač, Croatia
9th International Conference on Road and Rail Infrastructure

DEEP SOIL STABILIZATION IN TRANSPORTATION INFRASTRUCTURE USING INDUSTRIAL BY-PRODUCTS: THE CIRCUIT PROJECT FRAMEWORK

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Abstract

Transportation infrastructure founded on peat and compressible clays frequently experiences excessive consolidation and creep settlements, leading to recurring maintenance interventions and increasing lifecycle costs. Conventional practice in the soil stabilization relies predominantly on cement- or lime-based binders. This study investigates the potential of industrial by-product ashes as alternative binders for soil stabilization, with particular emphasis on deep improvement techniques. By-product ashes originating from coal combustion, biomass incineration and metallurgical processes offer an opportunity to reduce reliance on primary binders while promoting circular material use. Within the CIRCUIT project, a systematic laboratory program will be conducted to evaluate mixtures of organic soils and various by-product binders, assessing strength development, stiffness evolution and environmental performance, including leaching behavior. The research is complemented by a field-scale application at the Oostmolendijk embankment in the Netherlands, where deep stabilization of peat layers is being investigated to mitigate long-term settlements. By integrating laboratory testing, numerical modelling, and on-site monitoring, the study aims to define an optimized, performance-based stabilization strategy that enhances subgrade resilience while reducing environmental impact.

Keywords: CIRCUIT project, soil stabilization, by-product ashes, sustainability

1 Introduction

Soil stabilization in transportation infrastructure is applied either in shallow or deep configurations depending on subsoil properties and project requirements. Shallow stabilization typically involves the upper 0.3–0.5 m of the subgrade and aims to enhance bearing capacity, reduce plasticity and increase resistance to frost and moisture variations. Being widely used in both road and railway construction, shallow stabilization primarily relies on prescriptive binder formulations using Portland cement or lime. Typical contents range from 2% to 5% by weight of dry soil, equivalent to roughly 50–100 kg of a binder per cubic meter of stabilized soil. Deep soil stabilization, including deep soil mixing or jet grouting technologies, is employed at greater depths to improve soft or highly compressible soils, particularly beneath embankments and heavily loaded corridors. In these applications, binder contents are generally higher, between 5% and 15% by mass [1]. While cement and lime provide predictable mechanical performance, their environmental footprint is substantial. Producing 1 kg of Portland cement consumes approximately 2 kg of natural raw materials, requires around 18 MJ of fossil energy, and generates roughly 1 kg of CO_2 [2]. Lime production consumes somewhat less energy, but its CO_2 emissions per kilogram remain comparable due to calcination. Consequently, even modest reductions in binder content per cubic meter of stabilized soil can yield significant environmental benefits.

DOI: https://doi.org/10.5592/CO/CETRA.2026.1959

The scale of earthworks in transportation infrastructure amplifies these impacts. In railway projects, earthworks, including subsoil stabilization, can account for roughly 20% of total costs on conventional lines and up to 50% for high-speed rail [3], with earthwork expenditures often reaching several million euros per kilometer. Similar trends are observed in road construction, where earthworks represent up to 30% of total project costs [4]. Under these circumstances, performance-based redesign of stabilization mixtures, incorporating industrial by-products such as ground granulated blast furnace slag (GGBFS), fly ash, recycled construction and demolition materials, or geopolymers, offers potential to reduce both environmental impact and project cost. The use of recycled or secondary materials in the stabilization mixtures remains limited, with cement and lime continuing to dominate. Experimental and pilot studies have explored waste and by-product additives, but widespread application is still uncommon. However, over the past two decades, the use of industrial by-products in soil stabilization has received growing attention as part of efforts to lower the environmental footprint of infrastructure construction [5]. Research has focused on materials with latent hydraulic or pozzolanic activity capable of partially or fully replacing cement or lime in soil stabilization applications.

This paper gives the overview of the use of industrial by-products for deep soil stabilization and illustrates an ongoing case study aimed at optimizing subgrade stabilization at the Oostmolendijk embankment in the Netherlands. The research is conducted under the Horizon Europe CIRCUIT project [6] and focuses on identifying an optimal binder composition that maximizes the use of by-product ashes while maintaining adequate mechanical performance and durability.

2 Overview of the by-product usage in deep soil improvement

Soil stabilization can be accomplished by several methods, which broadly fall into mechanical and chemical approaches [7]. Mechanical stabilization alters the physical properties of the soil through compaction, vibration, or reinforcement, and will not be discussed here. Chemical stabilization relies on reactions between cementitious binders and soil minerals to enhance strength, stiffness and durability. Among chemical stabilization techniques, deep soil mixing (DSM) and jet grouting (JG) methods, figure 1, are the most commonly applied. DSM involves the in-situ blending of binders, such as cement, lime, or combinations thereof, with the native soil using specialized mixing tools. Depending on binder consistency and soil properties, DSM can be performed using dry or wet mixing methods. JG in contrast, creates cemented soil columns by injecting high-pressure grout into the ground while simultaneously rotating and withdrawing the drill rod. The choice of technology is critical for soft and highly compressible soils. Problematic soils such as peat exhibit high compressibility, low strength, low permeability, and volume instability, where under such conditions, DSM and JG offer an economically attractive alternative to mechanical methods. These methods reduce moisture content, increase stiffness, strength and compaction properties, and mitigate shrinkage and swelling.

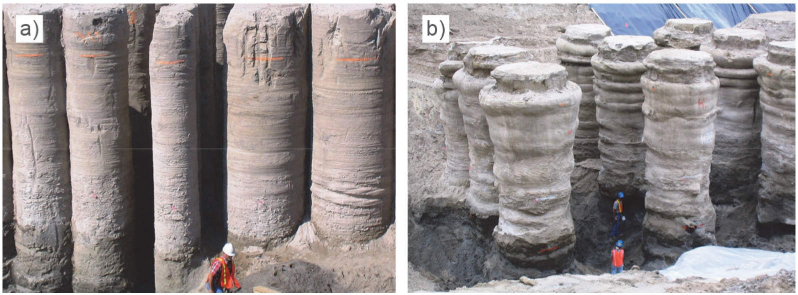

Figure 1 Excavated deep soil mixing columns (a) and jet-grouting columns (b), obtained from [8], constructed as part of the Tuttle Creek Dam project

Fine-grained soils are generally easier to stabilize due to their large surface area. Clays have flat, elongated particles that facilitate chemical reactions, while silty soils are sensitive to moisture variations, complicating stabilization. Organic and peat soils, as the ones prevailing at the CIRCUIT case study, are particularly challenging, as having high water content, high porosity, and variable consistency, sometimes extending several meters below the surface. High organic content can hinder binder hydration, since calcium ions are retained by soil exchange capacity, reducing pH and delaying cementitious reactions [7]. However, few field studies in Europe have demonstrated successful stabilization of clayey and organic soils with lime-cement columns [9]. Recent research has increasingly explored industrial by-products such as fly ash and GGBFS as partial or full substitutes for cement or lime in soil stabilization. Laboratory investigations indicate that these materials, used independently or in combination with traditional binders, can substantially enhance strength, stiffness, and durability while simultaneously reducing environmental impact [5]. Nevertheless, practical implementation remains predominantly associated with shallow stabilization, while documented large-scale applications in DSM or JG are still comparatively limited. This can be attributed to the additional complexities inherent to deep stabilization, including control of mixing energy, achieving homogeneous binder distribution at depth, and addressing scale effects that are not adequately captured in small-scale laboratory programs.

Despite these challenges, several studies demonstrate the technical feasibility of incorporating by-products in deep applications. Cristelo et al. [10] reported that alkaline-activated fly ash used in deep stabilization achieved unconfined compressive strengths up to 43.4 MPa after 365 days of curing, while field JG applications reached 26.4 MPa at 90 days, confirming its potential for large-scale implementation. Hansson [11] showed that substitution of up to 70% of lime and cement with fly ash in DSM can produce strengths exceeding those of conventional mixtures, while partial substitution around 30% maintains approximately 80% of the reference strength. Similarly, Arulrajah et al. [12] demonstrated that fly ash–slag geopolymer binders significantly improved strength and stiffness in soft marine clay treated by DSM, with optimum binder contents of approximately 20%. Yenginar and Olgun [13] further optimized cement–fly ash–superplasticizer grout compositions for deep mixing columns in high plasticity clayey soil, achieving higher strength and lower permeability. Field-scale dry DSM trials using GGBFS and red gypsum have also shown performance comparable to Portland cement stabilization of peat deposits without requiring equipment modification or reduced production rates [14]. More recently, Shi et al. [15] investigated soft clay stabilization using cement, GGBFS and Terrazyme with a contra-rotational shear DSM technique, demonstrating improved column uniformity and integrity in large-diameter deep stabilization. While these studies confirm that industrial by-products can partially replace traditional binders in deep soil stabilization and their feasibility has been demonstrated in selected cases, systematic performance-based frameworks integrating mixture optimization, execution technology, long-term durability, and environmental assessment under real infrastructure conditions remain insufficiently developed.

3 Framework for deep soil stabilization within the CIRCUIT

3.1 Overview of the case-study area

The densely populated and highly industrialized western part of the Netherlands is underlain by highly compressible Holocene soft clay and peat deposits. In this low-lying deltaic environment, relative sea-level rise represents a significant long-term hazard. However, regional land subsidence currently exceeds mean sea-level rise rates, with measured ground surface lowering typically ranging between 7 and 13 mm per year [16]. This accelerated subsidence is primarily driven by groundwater level management practices required for agricultural use

and urban development. Continuous groundwater pumping induces consolidation of soft clay layers and oxidation-driven volume reduction of peat, both of which contribute to ongoing settlement. Climate change introduces additional stressors to this already vulnerable system. Within this geotechnical and climatic context, critical infrastructure elements, including roads and railways, are predominantly constructed on embankments and dykes extending over thousands of kilometers. Progressive settlement and lateral deformation of these structures constitute a major long-term maintenance and safety challenge.
The present study focuses on a section of the Oud-IJsselmonde–Oostendam flood protection system, located between Rotterdam and Dordrecht, figure 2. This 9.4 km-long embankment, consisting of engineered soil slopes, protects the eastern part of IJsselmonde from hydraulic loading from the Noord River and also functions as a road embankment. Within this system, the Oostmolendijk section is particularly critical due to ongoing long-term settlements. Previous investigations [17] have identified the low shear stiffness of the underlying peat and soft clay deposits as a primary driver of creep settlements and lateral spreading. Observed distress includes cracking along the crest, time-dependent differential settlements, and progressive outward displacement of the slopes, figure 2.

Figure 2 Oostmolendijk location & example of observed deformations and cracks

Current maintenance practice consists primarily of periodic crack sealing and heightening of the embankment to maintain required safety levels. However, such measures do not address the underlying geotechnical mechanisms. On the contrary, the repeated addition of fill material increases vertical stress, thereby accelerating consolidation and long-term settlement. As a result, several sections now require structural upgrading rather than routine maintenance.

3.2 Baseline studies and settlement rate quantification

Progressive, time-dependent, settlement of embankments constructed on soft deposits represents a long-recognized challenge in the Netherlands. Earlier studies addressing the performance of Dutch flood defences have shown that many embankments gradually lose elevation due to the combined effects of subsoil consolidation, creep of peat and soft clay layers and relative sea-level rise [18]. In the case of the Oostmolendijk, historical records indicate substantial cumulative settlements over the past decades. Following the first elevation works in the late 1960s, approximately 0.60 m of settlement was recorded by the early 1980s, with an additional 0.15 m occurring during the subsequent decade [18]. A second crest raising was performed in the early 1990s.

Despite these interventions, continued deformation was observed after later reconstruction works, including additional fill placement on the crest and downstream slope. These observations have raised concerns regarding the conventional strategy of repeated crest heightening. To better understand and quantify the time-dependent behavior of the Oostmolendijk, a study by Kovačević et al. [17] focused on the identification of creep parameters governing long-term deformation of the soft foundation soils. Recognising the limitations of conventional laboratory creep testing, both in terms of duration and cost, the authors developed an inverse modelling framework based on Burger's constitutive law. The approach combined numerical simulations with machine learning techniques to estimate the most probable set of creep parameters controlling embankment settlements. The methodology integrated multisensor field data (MASW, CPT, ERT) into a calibrated numerical model of the embankment–subsoil system. Continuous monitoring data obtained from InSAR and GPS measurements of long-term displacements were employed to calibrate and validate the predictive framework. The prediction model yielded long-term settlement estimates that were 20–35% lower than those obtained using conventional statistical regression methods extrapolated over the same period. The optimized model enabled reproduction of the measured settlement history and provided improved long-term settlement predictions.

3.3 Concept of the proposed stabilization approach

While various upgrade strategies are available in practice, each requires careful evaluation of technical feasibility, effectiveness, and cost–benefit performance. Existing intervention methods predominantly target ultimate limit states and typically involve structural measures such as piled reinforcements or retaining systems. Although these solutions can ensure global stability, they are often costly and carbon-intensive, and their effectiveness in addressing long-term serviceability issues, such as creep and progressive subsidence, remains uncertain. Within the framework of the CIRCUIT project, the research focuses on the development and laboratory evaluation of innovative binder mixtures for deep soil improvement. The aim is to define an optimal mixture for highly organic subsoils, maximizing the proportion of industrial by-product binders while reducing the use of primary lime and, where possible, cement. Environmental performance is also a key criterion, and leaching tests are included to ensure compliance with relevant regulations.

The implementation strategy consists of two main steps. First, soil samples from critical areas will be used in laboratory tests to evaluate the effectiveness of different by-product mixtures in increasing soil strength and stiffness, including leaching assessments. Laboratory experiments are conducted under controlled conditions using a range of binders sourced from the Netherlands, including standard cement, lime, fly ash, GGBFS, biomass ash, along with some innovative additives such as the Novocrete. Organic soil samples were obtained on-site through continuous coring, and representative samples of the soft peat layers are shown in figure 3. The most efficient and environmentally optimal solution will be incorporated into a numerical model to predict improvements and the mitigation of long-term subsidence over the Oostmolendijk lifetime.

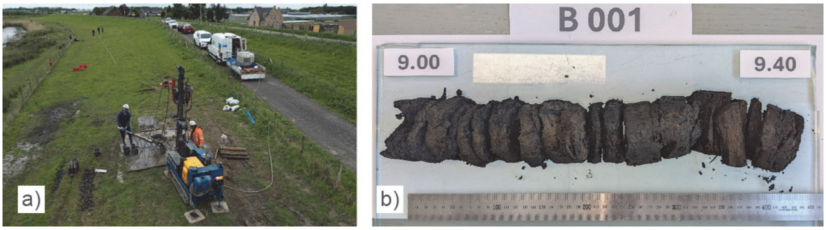

Figure 3 Sampling at Oostmolendijk (a) and representative peat sample (b)

Second step includes large-scale implementation at the Oostmolendijk site, which provides a representative and strategically relevant field setting for testing alternative ground improvement strategies. The proposed solution employs in situ DSM to enhance the mechanical properties of the soft clay and peat deposits. Although the selection of the optimal execution method is ongoing, DSM currently appears to be the most promising candidate. The evolution of strength and stiffness over time will be monitored using CPT and shear wave velocity measurements. Preliminary field investigations at the Oostmolendijk have already been conducted using CPTs and geophysical methods, producing profiles that identify weaker layers within the organic subsoil. Subsequent measurements along the same profiles after stabilization will quantify improvements in soil stiffness and strength.

4 Conclusion

Industrial by-products such as fly ash, ground granulated blast furnace slag and biomass ash demonstrate significant potential to partially replace cement and lime in deep soil stabilization, offering reductions in carbon emissions and primary material use while maintaining adequate mechanical performance. Although laboratory and selected field studies confirm their technical feasibility, systematic performance-based frameworks that integrate mixture optimization, durability, environmental compliance, and field implementation remain limited. The case of the Oostmolendijk section within the Oud-IJsselmonde–Oostendam flood protection system in the Netherlands highlights the limitations of conventional strategies based on repeated crest raising, which do not address creep-driven settlements of peat and soft clay. Long-term serviceability, particularly stiffness enhancement and reduction of time-dependent deformations, must therefore become a primary design objective. Within the CIRCUIT project, an integrated approach combining laboratory testing, leaching assessment, numerical modelling and field-scale deep soil mixing is being developed to define an optimized binder composition with a high share of by-product materials. This framework supports the transition toward resilient, performance-based and environmentally responsible ground improvement solutions for infrastructure on highly compressible soils.

Acknowledgments

This research is conducted within the CIRCUIT (Holistic approach to foster circular and resilient transport infrastructures and support the deployment of green and innovation public procurement and innovative engineering practices) project, funded by the European Union’s Horizon Europe Innovation Programme under grant agreement No 101104283.

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