



Original article

# Stress-strain behavior of railway embankments stabilized with grouted micropiles

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## ARTICLE INFO

### Keywords:

Rail trackbed stabilization  
Railway embankment  
Jet-grouting  
Ground improvement  
Finite element method  
Numerical analysis

## ABSTRACT

Excessive ballasted track deformations may occur during the railway operations due to poor load bearing capacity of the embankment (placed soil or natural ground) or the manifest accumulation of subsidence caused by the soil consolidation and the passage of trains. The principles of pressure grouting (or jet-grouting) technologies, used to create reinforcement elements for the rail trackbed stabilization, are presented, with reference to the specific construction condition on an existing and in-service railway track. A single-track railway, including the superstructure and substructure components, was modeled using the finite element method (FEM). Some soil stabilization options, based on the installation of grouted micropiles according to different layout configurations, were considered. The results of the numerical analyses, in the form of stress and strain behavior of the whole track structure, demonstrated that the use of jet-grouted micropiles is a rational and less expensive option, which can be installed on or close to the track, having positive effects on limiting the vertical deformations of the embankment without affecting the expected distribution of stress states in the embankment middle.

## 1. Introduction

One of the most significant problems of railway maintenance is the cost reduction for the subgrade reconstruction and repair in compliance with the parameters of its strength, stability, reliability and durability [1,2]. The preservation of the designed vertical alignment of the rail, which is a stringent parameter with respect to the rail network hierarchy and the line classification, is essential to ensure traffic safety and to maintain the efficiency and integrity of the railway facilities. Design errors in qualifying the bearing capacity of the soils or, more often, the production of excessive vertical deformations caused by the time and/or the passage of trains, may require costly rail trackbed reinforcement or stabilization associated with important operational and economic consequences. When the stabilization concerns the deeper layers, vertical rail adjustments and frequent ballast tamping are temporary, if not ephemeral, solutions. Requirements for the embankment strength and stability become constantly higher and dictate the need to develop modern ground improvement solutions [3,4]. As a general rule, enhancing the stability and load-bearing capacity of the ground of a railway embankment is conceptually based on two approaches, which are strictly related to the geometric arrangement of the reinforcement

elements in the soil matrix. The first approach suggests strengthening the soil with horizontal elements, whereas the second one is instead based on the use of vertical (and sometimes inclined) elements.

According to the geometric arrangement of the reinforcement elements in the embankment, these two concepts offer a rather different range of options. It should be noted that the use of horizontal elements is historically more ancient, so its development is more detailed. It generally implements two options: reinforcement using geosynthetic materials [5–7] or protective layers [8,9] (layers of low-deformable material, sub-ballast, etc.). Geosynthetic materials (geotextile and geogrids), which are horizontal reinforcement elements, are modified materials that have been successfully used for several decades in several European countries [5,10,11] (Fig. 1).

For example, the strengthening of the embankment with horizontal elements in Ukraine is reported in the national standard "TsP-0204 Rules for the design of the main site of the embankment overall repair and modernization of the track" [12]. However, the strengthening with geosynthetic materials has recently been subject to constructive criticism [6,13,14]. Some disadvantages related to this method are increasingly noted: 1) the possibility of installing a horizontal element of reinforcement (geotextile or geogrid) only during overall repair or

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<https://doi.org/10.1016/j.aej.2024.05.088>

Received 4 January 2024; Received in revised form 9 April 2024; Accepted 26 May 2024

Available online 4 June 2024

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reconstruction of the embankment; 2) some difficulties during the current operation of the embankment reinforcement with geosynthetic materials; 3) low influence of the horizontal reinforcement element on the reduction of the vertical component of the deformation. The last drawback is significant in the railway context since the vertical component induced by the rolling stock is the main reason for the deformations development [15,16]. Thus, the main function of geosynthetic materials, as evidenced by several studies [13,17], has progressively shifted from a reinforcing role to a separating purpose, preventing the penetration of ballast into the embankment. The second option, i.e., the use of protective layers, involves the application of horizontal elements having similar properties to the embankment soil. Specifically, they are protective soil layers or layers of slightly deformable material [8–10]. Their application, in contrast to the reinforcement with geosynthetic materials, is based on increasing the overall deformation modulus of the system. Protective layers offer a more controlled effect since there are no incorporations in the soil embankment. A typical example in the rail track application is the sub-ballast, which is generally composed of broad-graded granular material or asphalt-based mixes. This layer, in addition to reduce the traffic induced stress at the bottom of the ballast to a tolerable level for the top of the subgrade and extend the subgrade frost protection, fulfills several important functions (e.g. keep the subgrade and ballast separate, prevent upward subgrade fines migration and subgrade attrition by ballast, shed water from above and drain water from below, etc...) [18]. Starting from the findings of previous research [6,9], it is possible to conclude that the low-deformable layer and the reinforcement in the form of geotextile or geogrid embedded into the soil matrix have radically different effects on the stress-strain state of the embankment, although their impact integrally consists in reducing its deformations. At the same time, the impact of the low-deformable layer and geosynthetic materials should be clearly distinguished. A low-deformable layer, due to an increase in its deformation modulus, reduces the deformations of the system in general, increasing its deformation properties. However, this increase occurs only in the layer and in its proximity; it is based only on the increase in deformation properties (not on the friction coefficient or specific adhesion, etc). Such layer is deformed together with the soil matrix in which it is placed, in such a way that no delamination, cracks and continuity violation of the model are observed, in contrast to the geotextile reinforcement.

In recent decades, strengthening the embankment with vertical elements has appeared and is gradually developing worldwide [19–22], using piles or columns installed according various technologies (grouted, drilled, bored and screw piles, etc...) [23–26] (Fig. 2).

Although the length of piles can be reduced, the role of these vertical elements remains unchanged [27–29]. Thus, the main current trend is the application of micropiles [14,30–34]. If necessary, soil-cement piles can be reinforced both in the upper part and along their length, using pipes, reinforcing bars, space frames, I-beams, channels, etc... [35–37]. Moreover, reinforcement can be performed in the first hours before the setting of the soil-cement material by the usual immersion of the reinforcement elements. The choice of the creation technology, i.e., the selection of the injection range of the soil-cement solution, is still being discussed and several injection types are adopted (with low, medium and high pressure) [38–40].

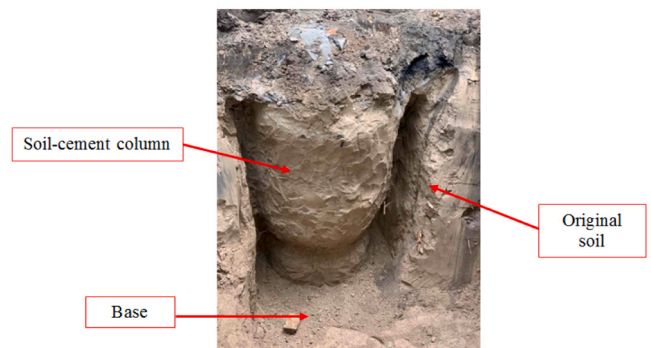


Fig. 2. The general view of the soil–cement column (photo from [19]).

In addition to the two fundamental described techniques (horizontal and vertical reinforcements), there are additional alternatives, which have developed over time by combining the basic interventions: geosynthetic materials combined with a low-deformable layer [6,10] or geosynthetic materials [6,7,14] combined with pile reinforcement [12, 13,17]. The emergence of such mixed solutions opened the possibility of creating new structural reinforcement solutions (for example, Geosynthetic-Reinforced-Pile-Supported (GRPS) – a combination of geogrid and piles), some of which have proven to be quite effective but require clarification of the construction technology [13,17]. By way of an example, the combination of geosynthetics with piles is carried out in a GRPS system (Fig. 3) was widely studied by Alsirawan [17].

Recently, chemical soil consolidation, in particular cementation, has been widely used to strengthen the embankment. The essence of this method is to inject a cement mortar into the pores of the soil, the hardening of which significantly increases the strength of the base. Jet grouting technology and boring and mixing technology are the most common types of cementations [41–44]. The essence of jet grouting is that the soil is mixed by a high-pressure jet of the cement mortar [24, 25]. The jet flows under high pressure from the monitor located at the lower end of the drilling string. Installation of micropiles according to jet grouting technology is performed in two stages: direct (well drilling) and reverse run of the drilling string. In the process of the reverse run, the pile is lifted with its simultaneous rotation. At the same time, the pressure of the cement mortar entering the monitor nozzles is increased, creating a jet with high kinetic energy [21,22]. The fundamental difference between boring and mixing technology and jet grouting is that the pressure of the cement mortar is ten times less [33,44]. The digging of the soil is occurred not by jet, but by a special chisel or impeller. The cement-sand mortar acts as a binder (Fig. 4).

Accordingly, the strength and deformation characteristics of micropiles created by boring and mixing technology are less than by jet grouting. This, in turn, requires a greater number of elements to obtain the desired reduction in deformation. The most important advantage of jet grouting is the ability to drill in narrow spaces (for example, between sleepers) (Fig. 5). In this case, the design diameter of the piles does not depend on the distance, because the vertical element is formed below the rail-and-sleeper grid, and the drill string is easy enough to pull from even between the sleepers. Moreover, it is possible to form vertical

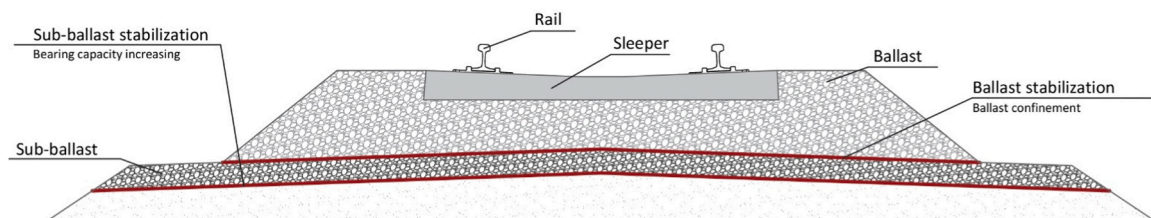


Fig. 1. Installation of horizontal reinforcement in a ballasted rail track.

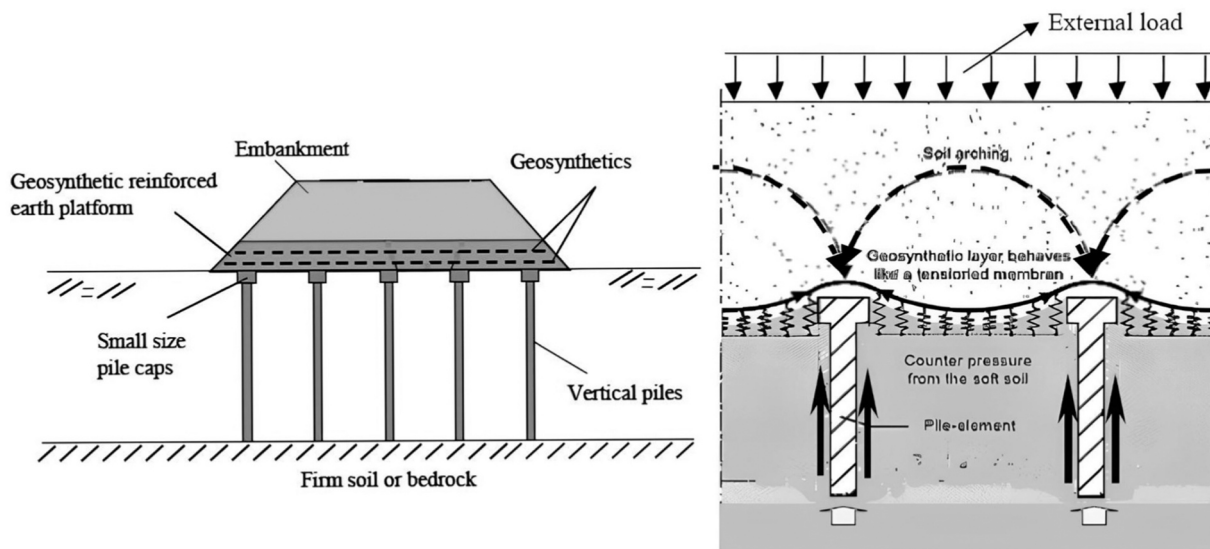


Fig. 3. Scheme of the arrangement of Geosynthetic-Reinforced-Pile-Supported (GRPS) (photo from [17]).



Fig. 4. Drilled core samples of grouted micropiles.



Fig. 5. Jet grouting technique for railway soft-subgrade soils stabilization.

elements with a diameter ranging from 0.2 to 1.5 m in the soil mass using this technology. In the case of micropiles with a length of up to 6.0 m, a small diameter (0.20–0.30 m) can be adopted.

The scientific literature on the impact of soil-cement piles and micropiles on the stress-strain state of a soil matrix followed three lines of research. The first direction is theoretical [45–48]. It is based on mathematical relations between the application of static or dynamic loads on the embankment and its deformations. The second direction,

which is based on specific on-field research, is experimental [28,29,36, 49–51]. Without deeply analyzing these directions, they differ in significant financial costs regardless their effectiveness. A third direction is currently the main used. It is based on numerical analyses using the finite element method (FEM) [6,14,32,44,52–56]. This approach cannot be considered universal, but it is a primary that allows to refine theoretical and experimental research. The FEM modeling of grouted piles could represent a well suited solution for a preliminary analysis, due to optimization costs and to display actual different potential operational problems that may occur along a railway line that needs rehabilitation actions to overcome embankment failures. Thus, the authors propose an approach based on the comparative evaluation of the potential effectiveness of grouted micropiles performed close to the railway track, placed alongside or between the railway sleepers. Each alternative can lead to specific effects on the surrounding embankment soil, depending on the loads induced by the structure's own weight and the train passage.

## 2. Methods

### 2.1. Models creations and prescribed conditions

Numerical models were created to assess the influence of grouted micropiles on the stress-strain state of the railway embankment using the integrated system for finite element structural analysis Structure CAD Office® (Scad Soft). Specifically, the algorithm of automatic triangulation in the complex was applied [44]. “Triangular prism” and “tetrahedron” finite elements were selected in the software library. These are isoparametric elements with a maximum size of  $0.2 \times 0.2 \times 0.2$  m (there are elements with a size of  $0.25 \times 0.25 \times 0.25$  m, not more than 7% of the total number of finite elements in the model). These finite elements are compatible, i.e., all nodes of neighboring elements coincide, ensuring a positive effect on the analysis accuracy. The 2D FEM mesh has 46314 finite elements and 70149 nodes (about 211 thousand degrees of freedom, the task is considered a large-scale one). The sizes of the model are taken from the real cross section of a single-track railway (ballasted track). Due to the scale of assessment and the types of the reinforcement techniques (deep methods), the ballast bed in the FEM model was placed, as a first approximation, on a single thick layer (4000 mm), labeled embankment, which includes the sub-ballast and formation layers. Literature values were used for the input physical parameters of the system elements and materials (Table 1).

**Table 1**  
Stress-strain properties of the finite elements of the model.

Model element name	Modulus of elasticity $E$	Poisson's ratio $\nu$	Specific gravity $\gamma$
	[kPa]	[-]	[kN/m <sup>3</sup> ]
Rail (steel)	$2.1 \cdot 10^8$	0.3	77.0
Sleeper (reinforced concrete)	$4.0 \cdot 10^7$	0.2	25.0
Ballast (crushed stone)	$10 \cdot 10^4$	0.2	22.0
Embankment (silty and clayey soil)	$25 \cdot 10^3$	0.3	19.0
Jet-grouting column	$25 \cdot 10^5$	0.2	23.0

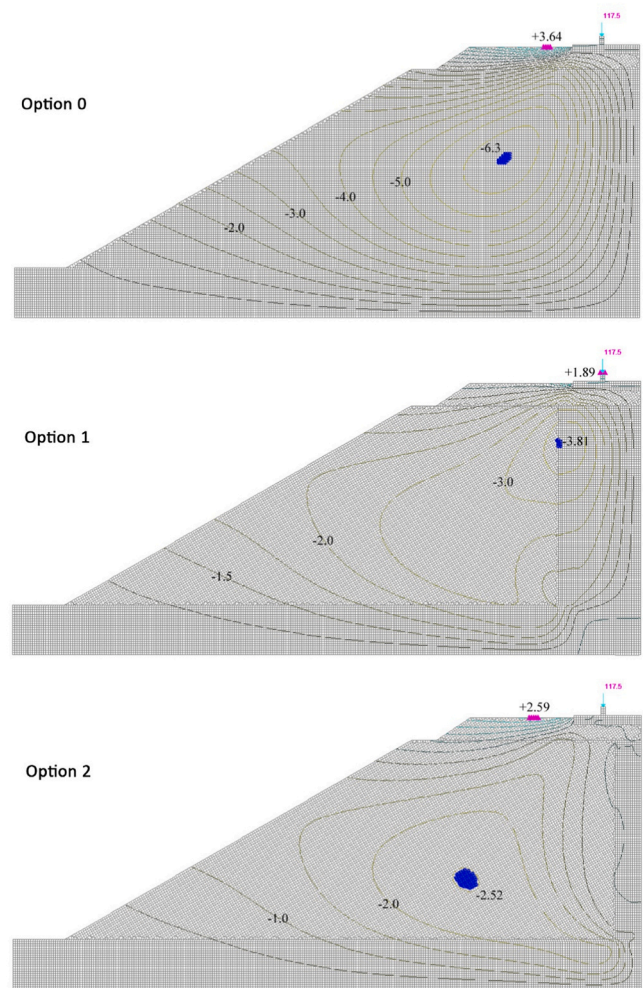
Three options were modeled (Fig. 5): Option 0 – without strengthening; Option 1 – strengthening with jet-grouted micropiles located near the sleeper; Option 2 – strengthening with jet-grouted micropiles located near the rail (inside the rail-and-sleeper grid). Jet-grouted micropiles with a diameter of 0.3 m and a length of 4 m were adopted as strengthening elements. Since a further potential option, i.e., strengthening with vertical elements located outside the ballast prism, resulted less effective in a previous study by Tiutkin et al. [44], this solution was not modeled in this document.

Kinematic boundary conditions were set according to geometric constraints. The lower part of the system has translation constraints in z and x direction and a symmetry boundary condition exists on the right side of the model. The load configuration aims at analyzing the short-term behavior of the railway system subjected to the load induced by a train. Specifically, the static application (concentrated) of a train wheel on the rail was considered: starting from an axle load of 24 tons (freight wagon), each rail is loaded by 117.5 kN. The analysis of the stress-strain behavior of the system consisted in the quantitative determination of displacements and stresses in six characteristic points. Specifically, displacement components were measured in points 1–4, and stress components in points 4–6 (Fig. 6).

### 3. Results and discussion

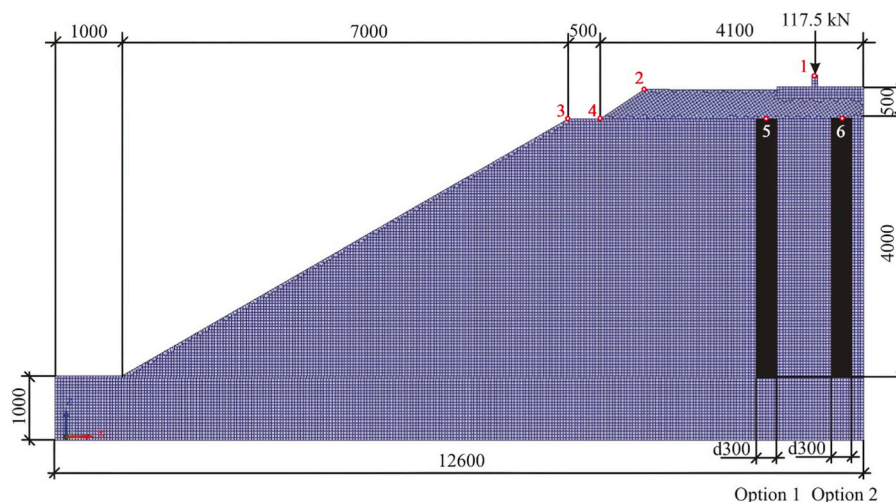
Fig. 7 shows the results of the numerical analysis in the form of horizontal displacement isolines induced by the train wheel load. The values of the characteristic isolines, which display the level of horizontal displacements distribution, are presented considering the deformed state.

Analysis from Fig. 7 reveals quite significant qualitative changes in the distribution of the horizontal stresses. The core of negative displacements changes its shape depending on the location of the jet-



**Fig. 7.** Isolines of horizontal displacements (0.5 mm step between isolines). Purple color = max. tensile area and blu color = max. compressive area.

grouted micropile. This pattern is explained by the fact that the soil stiffness ( $E_{\text{silty and clayey soil}} = 25 \cdot 10^3$  kPa) is one hundred time less than the stiffness of grouted material ( $E_{\text{soil cement}} = 25 \cdot 10^5$  kPa). The stiffness ratio changes the uniform pattern of displacements, the body of jet-grouted micropile reduces their value. Fig. 8 shows the changes in horizontal



**Fig. 6.** Scheme of the FEM model: Mesh and measuring points (1–6).

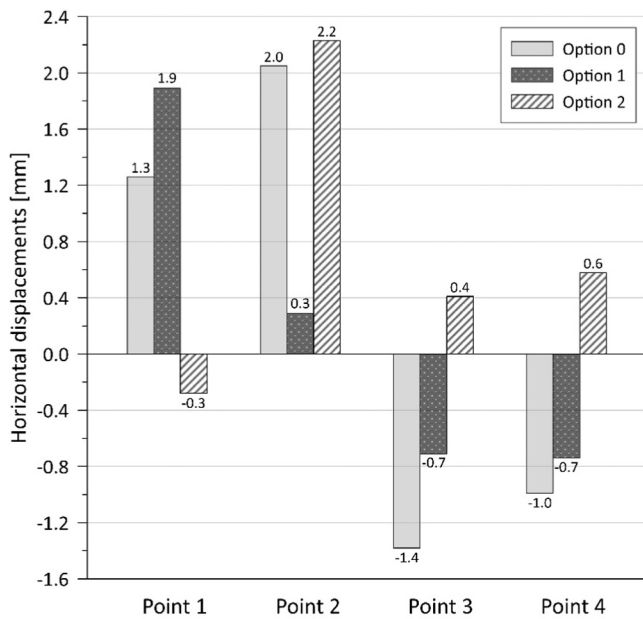


Fig. 8. Horizontal displacements at 1–4 points of the model.

displacements at the 1–4 points of the scheme. The most important region is the point 1, which is located on the rail and mostly characterizes the effect of the jet-grouted micropile positioning. Both options of strengthening somewhat reduce the magnitude of horizontal displacements. However, this result is a related effect. Considering for example the point 1, the horizontal displacements are 6.05 times less in Option 2 than in Option 0 (not strengthened embankment). The Option 1 produced increased horizontal displacements, reaching the value of 1.89 mm in contrast to 1.26 mm in Option 0. The Option 2, at the same time, dramatically changes the qualitative pattern of horizontal displacements (displacements change the sign to the opposite at points 1, 3, and 4), causing a slight jump at point 2 (2.23 mm versus 2.05 mm in Option 0). This outcome can be explained by the redistribution of stiffness and heterogeneity of the deformed state of the entire system.

Fig. 9 shows the results of the numerical analysis in the form of vertical displacement isolines induced by the train wheel load. The illustrations of the deformed state present the values of the characteristic isolines for comparing the level of vertical displacements. The critical reading of Fig. 9 suggests that the lower deformation limit (-4.0 mm isoline) is unchanged for all the three options. However, the next characteristic isoline (-16.0 mm isoline) moves up in Option 1, while it is located at the ballast-embankment interface in Option 2. The last characteristic isoline (with a value of -32.0 mm) is missing in both strengthening options, testifying a significant reduction in vertical deformation. Fig. 10 shows a diagram of the vertical displacements change, which is the most representative since the application of the jet-grouted micropile has logically the greatest impact on this displacement component. The bar graph (Fig. 10) highlights how both options significantly reduce the vertical displacements, above all at point 1 (rail head), i.e., 1.60 times in Option 1 and 1.96 times in Option 2. However, jet-grouted micropile strengthening reduce the vertical displacements also in the other points (2, 3 and 4): from 1.20 to 1.58 times in Option 1 and from 1.34 to 1.51 times in Option 2. The presence of the grouted micropile brings to a non-homogeneous deformed state and most affects in the zone of maximum development of deformations (the "core"), which is being formed around the rail-and-sleeper grid. Therefore, Option 1 (installation near the sleeper) is less effective in reducing vertical displacement: the element of greater stiffness is outside the zone of active deformation. Analyzing the vertical stresses, a significant peak (compressive stress of 3424.76 kPa), is observed at point 5 in Option 1 (Fig. 11). This is explained by the presence of a rigid body (jet-grouted

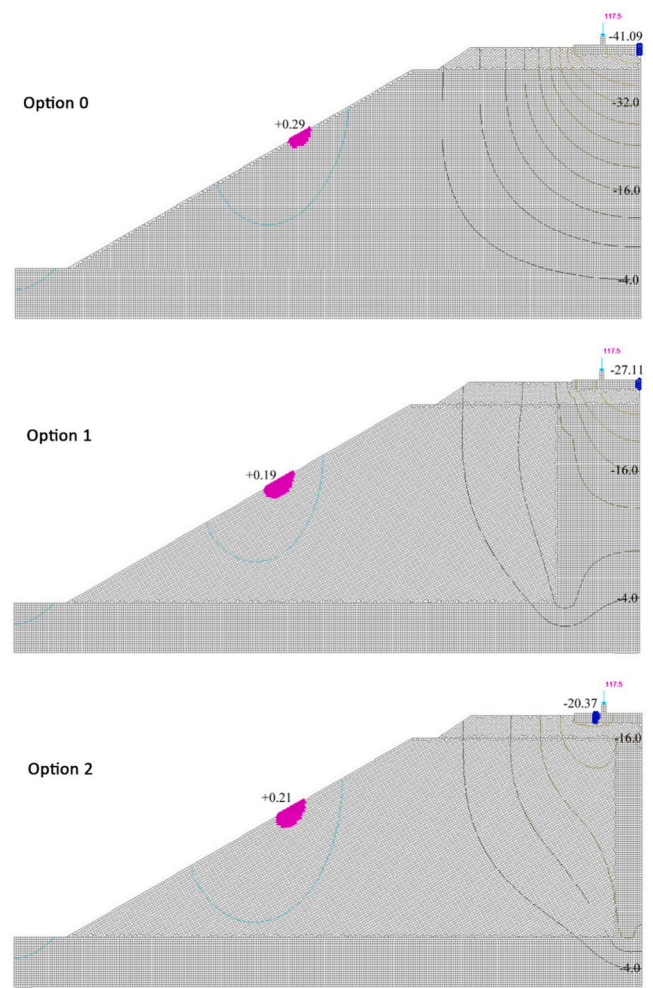


Fig. 9. Isolines of vertical displacements (4.0 mm step between isolines). Purple color = max. tensile area and blue color = max. compressive area.

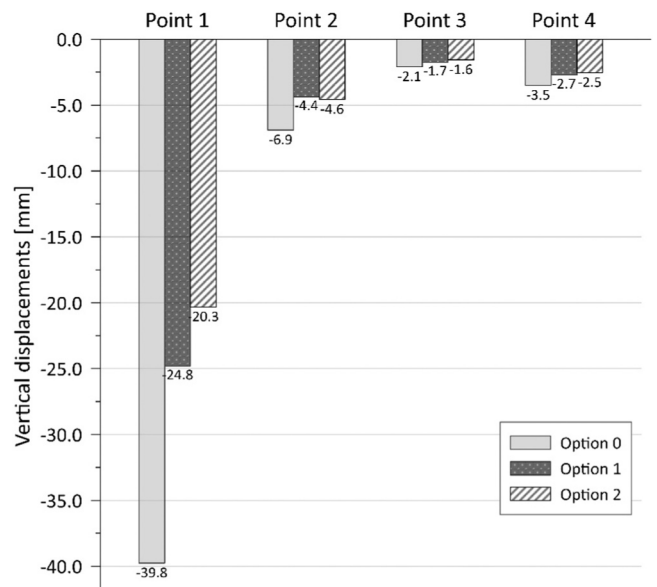


Fig. 10. Vertical displacements at 1–4 points of the model.

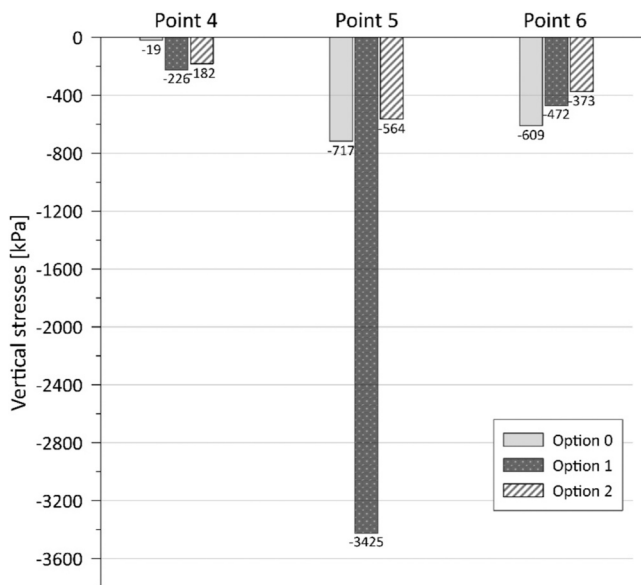


Fig. 11. Vertical stresses at 1–4 points of the model.

micropile) in this area. The sufficiently high-stress value is still less than the strength of the jet-grouted micropile and does not adversely affect its effectiveness. The active distribution of vertical stresses from the rail-and-sleeper grid goes together with the jet-grouted micropile and an over-stress (not observed in Option 2) occurs. It should be noted that the effect of Option 2 is minimal, indicating that the application of grouted micropiles near the rail does not disturb the tensional state under the sleeper at the center of the track.

#### 4. Conclusions

The optimization of the embankment-micropiles reinforcement relationship is an important problem in the design and implementation of interventions aimed at limiting the failure of existing and in-service tracks. Although the presented study is based on a specific case, it provides some useful comparative insights. The results of this analysis can be summarized in three main findings.

- The analysis of embankment strengthening technologies demonstrates that the use of jet-grouted micropiles is a rational and less expensive option, which can be installed on or close to the track, without major site preparation and without significant material movements.
- Jet-grouted micropiles having small length (~ 4 m) and diameter (~ 300 mm) can be placed close to and between railway sleepers (trackbed stabilization built on-track), with great logistical advantages. Their installation has positive effects on limiting vertical deformations of the embankment and does not appreciably affect the expected distribution of stress states in the embankment middle. In the proposed example, the specific position of the jet-grouted micropiles below the track sleepers reduces vertical displacements by 1.20–1.58 times. Values of vertical displacements (up to 20 mm) allow testifying to the normal operation of the embankment.
- Rapid systems are available for the on-track stabilization with high implementation productivity. This study provides an initial screening of the most effective techniques. A future scenario is the 3D modeling, which also offer the possibility to study the influence of the micro-piling layout configuration and to optimize their location along the track development.

#### Funding and Acknowledgements

Some of the research activities were funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of 16/12/2021 of Italian Ministry of University and Research funded by the European Union–NextGenerationEU. Award Number: Project code CN00000023, Concession Decree No. 1033 of 17/06/2022 adopted by the Italian Ministry of University and Research CUPD93C22000400001, “Sustainable Mobility Center” (CNMS), Spoke 4: “Rail Transportation”.

#### CRedit authorship contribution statement

**Federico Autelitano:** Visualization, Writing – original draft, Conceptualization. **Felice Giuliani:** Conceptualization, Funding acquisition, Writing – original draft. **Larysa Neduzha:** Conceptualization, Data curation, Methodology, Visualization, Writing – original draft, Supervision. **Oleksii Tiutkin:** Conceptualization, Data curation, Methodology, Visualization, Writing – original draft.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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