IOP Conference Series: Earth and
Environmental Science

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To cite this article: Ahmad Alkhdour *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1348** 012016

Regularities of the strain state of the embankment when varying the vertical element length of strengthening

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Abstract. The crisis that arose during the war in the transport system of Ukraine provided an opportunity to review the concept of integrating the Ukrainian railway into the European network. Corresponding changes, which require reconstruction of the railway, including track and embankment, have been analyzed. The railway embankment needs strengthening for its normal operation. The embankment reinforced with vertical elements, namely piles, has been studied. A finite-element model of the embankment, its soil base, and the rail-sleeper grid has been created. This model shows a vertical element of strengthening with lengths of 2.0, 4.0, and 6.0 m. The results of the numerical analysis are obtained, which makes it possible to analyze the values of horizontal and vertical displacements. The values of both components of the strain state are analyzed. The results of the analysis prove that strengthening with such elements has a maximally positive effect on both components of deformation. The regularities of changes in embankment displacements, when varying the vertical element length of strengthening, are linear. They prove that the presence of piles reduces the horizontal component by 1.1 ... 1.32 times, and the vertical one by 1.1 ... 1.24 times.

1. Introduction

Before the full-scale invasion of the Russian Federation, Ukraine played two main roles in the freight transportation system of the Eurasian continent [1]. Firstly, the railway system provided its own mining, metallurgical, agricultural, and other industries as a carrier. Secondly, the geographical position of Ukraine and its railway network provided opportunities for transit in the East-West direction [2]. Since the role of the transit country is currently not performed and may not be renewed in the next decades, the importance of the first role has increased significantly today.

Today, the railway of Ukraine in the role of a carrier is the most active player not only as a leading link of exports to Europe but also as an industry that provides high revenues to the budget of our country. This fact, as well as the fact that the railway is the main mode of transport for military transport, characterizes the relevance of new directions of its development.

The main vectors in the reconstruction of the Ukrainian railways have been outlined during the last ten years, but only by dotted lines. Although Ukraine was a transit country, and this role prevailed over the role of a carrier-exporter, however, some strategic directions were defined. After analyzing the current situation, it is possible to single out the main one, namely the integration of the Ukrainian railway into the transport system of the European Union [1].

After the opening of the Beskydy Tunnel in 2016, which increased freight transportation to the EU several times, this strategic direction was finally established and received some development, which was interrupted by the Russian Federation's war against Ukraine. Although the full-scale invasion somewhat slowed down the rate of changes in the field of combining the transport systems of Ukraine and the EU, it helped give birth to a radically new concept, which is no longer about integrating the Ukrainian railway into the European one, but about expanding the European railway to the East.

However, the problem of interoperability, that is, bringing two different systems to a common denominator, is still relevant. Interoperability mainly concerns four systems: 1) rolling stock; 2) energy supply; 3) automation and telecommunications; 4) railway track. There is no doubt that it is the fourth system that is the most significant since if the railway tracks and the embankment are not connected, then the other three systems do not have a foundation on which they are based.

Exactly the difference between the track gauge (1520 mm in Ukraine and 1435 mm in most countries of the European Union) that is holding back the implementation concerning the idea of developing a European railway in our country. It is clear that the simultaneous reconstruction of thousands of kilometers of Ukrainian track was impossible even in peacetime. However, if such work had been carried out at least in the border areas, then the enemy would have had catastrophic problems with logistics. If we consider a hypothetical situation in which a European gauge would be implemented over most of Ukraine, then this factor would be a barrier to military aggression.

Since the concept of the expansion of the European railway to the East cannot be fully realized, specific transitional solutions are emerging. Thus, the main one of them is the reconstruction of the Ukrainian track to a 1520/1435 mm dual gauge, for which special Sh2S-1 sleepers are designed and manufactured (figure 1) [1].

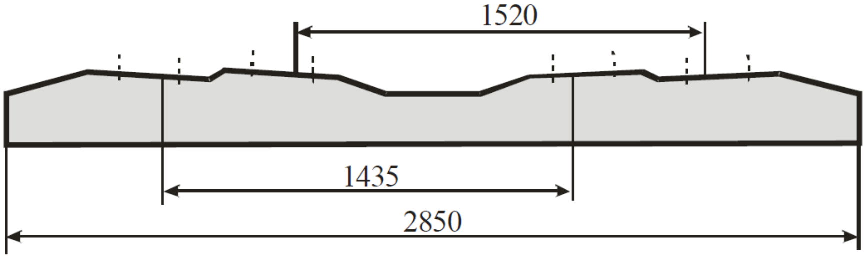


Figure 1. Scheme of reinforced concrete sleeper, type Sh2S-1 for the 1520-1435 mm dual gauge with rails, type P65.

This solution, in contrast to the method of changing bogies with a wheel gauge of 1520/1435 mm under the cars or creating special adjustable-gauge wheelsets, is the most rational, as it is capital and reliable [1, 2]. Also, the use of reinforced concrete sleepers of the Sh2S-1 type allows reconstruction into one line in the prospect, which has a European track gauge (1435 mm). Such a prospect, although it is considered to be a hypothetical one today, will make it possible to realize the concept of the expansion of the European railway to Ukraine.

However, there is a problem that is characteristic of Ukrainian railways now and will be exacerbated during the conversion to a dual gauge. This is a problem of embankment deformation under the action of train loads, which is expressed in excess displacements of the main platform and, accordingly, of the rail-sleeper grid. The solution to the problem is temporary and consists of repairing the track with underpinning ballast. In order to increase the time between repairs, the embankment should be strengthened.

At the moment, there are several directions for strengthening the embankment. Currently, the main direction is reinforcing with geosynthetic materials or by introducing slightly deformable layers [3, 4]. This classical direction of strengthening has recently been subjected to criticism, which can be considered successful if the issue of reducing exactly the vertical component of the embankment deformation is raised since horizontal reinforcement elements are effective precisely for reducing horizontal displacements [3, 5].

An alternative option for strengthening the embankment is a type of reinforcement by immersing vertical elements (piles or micropiles) [6, 7]. The idea of strengthening with piles or micropiles has been widely developed in many fields of construction [8, 9]. Its implementation for the embankment is based on drilling and mixing technology or jet-grouting [6-9]. An important issue is the placement of vertical elements and the determination of their effective parameters. The purpose of the scientific research is to determine the regularities of embankment deformation reinforced with vertical elements, namely piles.

2. Methods

The finite element method implemented in the SCAD complex (license number F755B84 (KMBKB RA 4810)) [10] has been used to determine the strain state of the reinforced embankment. A finite-element model of the embankment, its soil base, and the rail-sleeper grid has been created (figure 2).

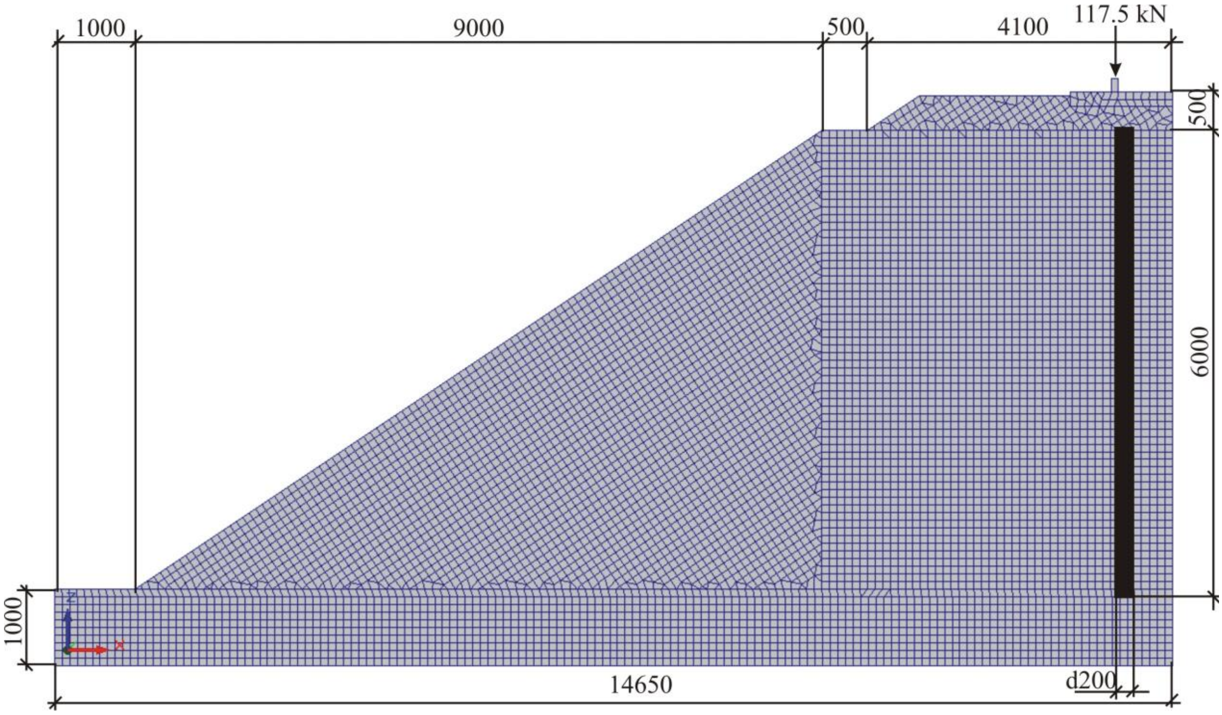


Figure 2. The finite-element model of the embankment with a height of 6 m for the track gauge of 1520 mm.

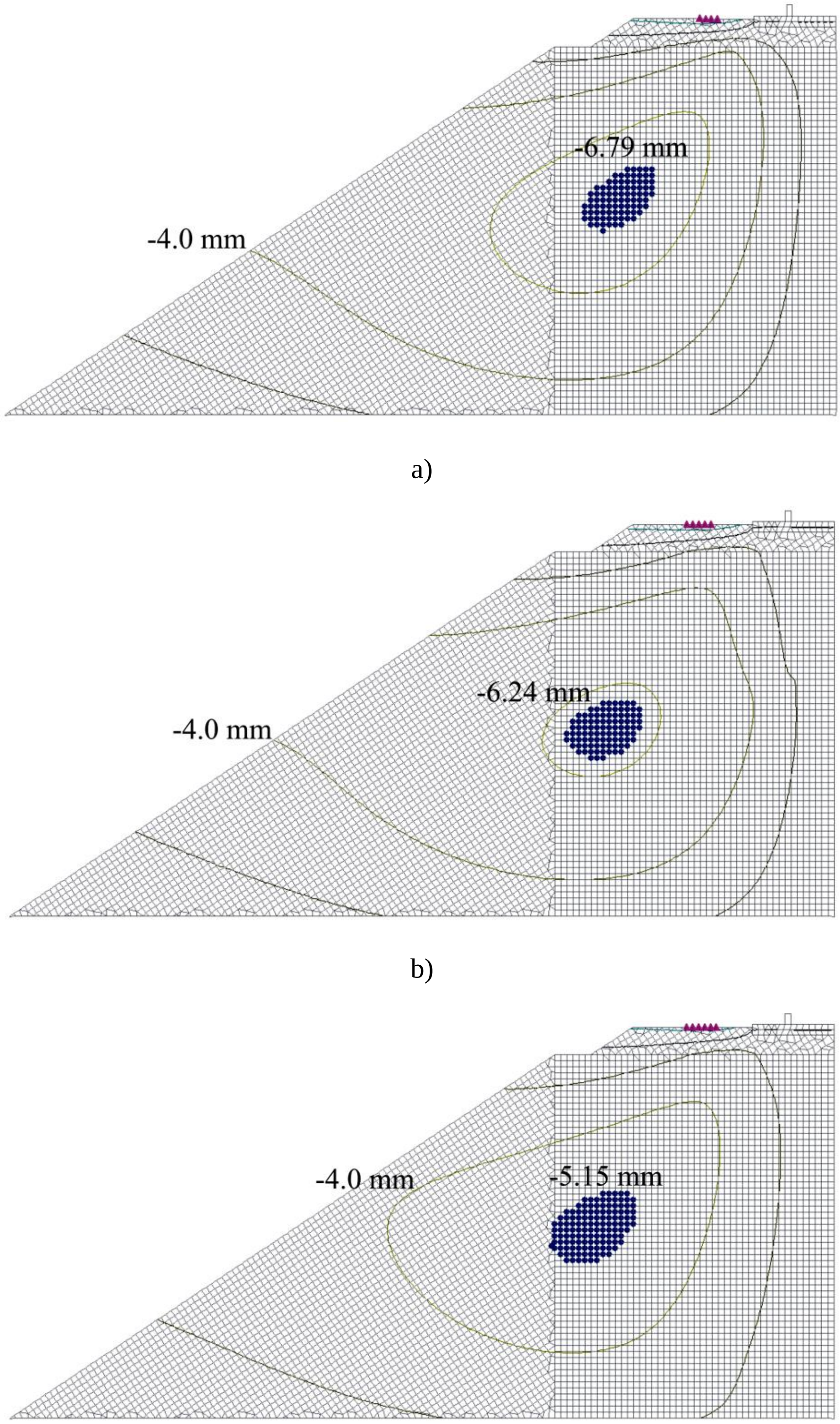
Strain characteristics (the elasticity modulus *E*) of the finite-element model are as follows: 1) rail (steel) E=2.1·10^8 kPa; 2) sleeper (ferroconcrete) E=4.0·10^7 kPa; 3) ballast (crushed stone) E=10·10^4 kPa; 4) embankment (weak clay loam) E=25·10^3 kPa; 5) pile (soil cement armored with a steel carcass) E=140·10^5 kPa.

The installation of a pile with a diameter of 0.2 m in exactly this position is based on the results of the study [9], as well as on the technological capabilities of the drilling unit, which can carry out drilling without removing the rail-sleeper grid. The diameter of the pile researched within the framework of this article is considered reduced since most often the range of diameters varies between 0.3 ... 1.2 m.

The model was loaded forcefully with 117.5 kN on the rail, which is half of the train load. After the creation of the models, a numerical analysis was carried out.

3. Results and discussion

The obtained results of the numerical analysis made it possible to get the values of horizontal (figure 3) and vertical (figure 4) displacements for four options (without a pile, with a pile, length of 2.0, 4.0 and 6.0 m). Results for a vertical element with a length of 4.0 m are not shown to save space, but the displacement data for this option is analyzed below.



a)

b)

c)

Figure 3. The strain state of the embankment (horizontal displacements, mm; the step of the isolines is fixed and is 2.0 mm) with pile reinforcement with a length of a) 0 m (unreinforced); b) 2 m; c) 6 m.

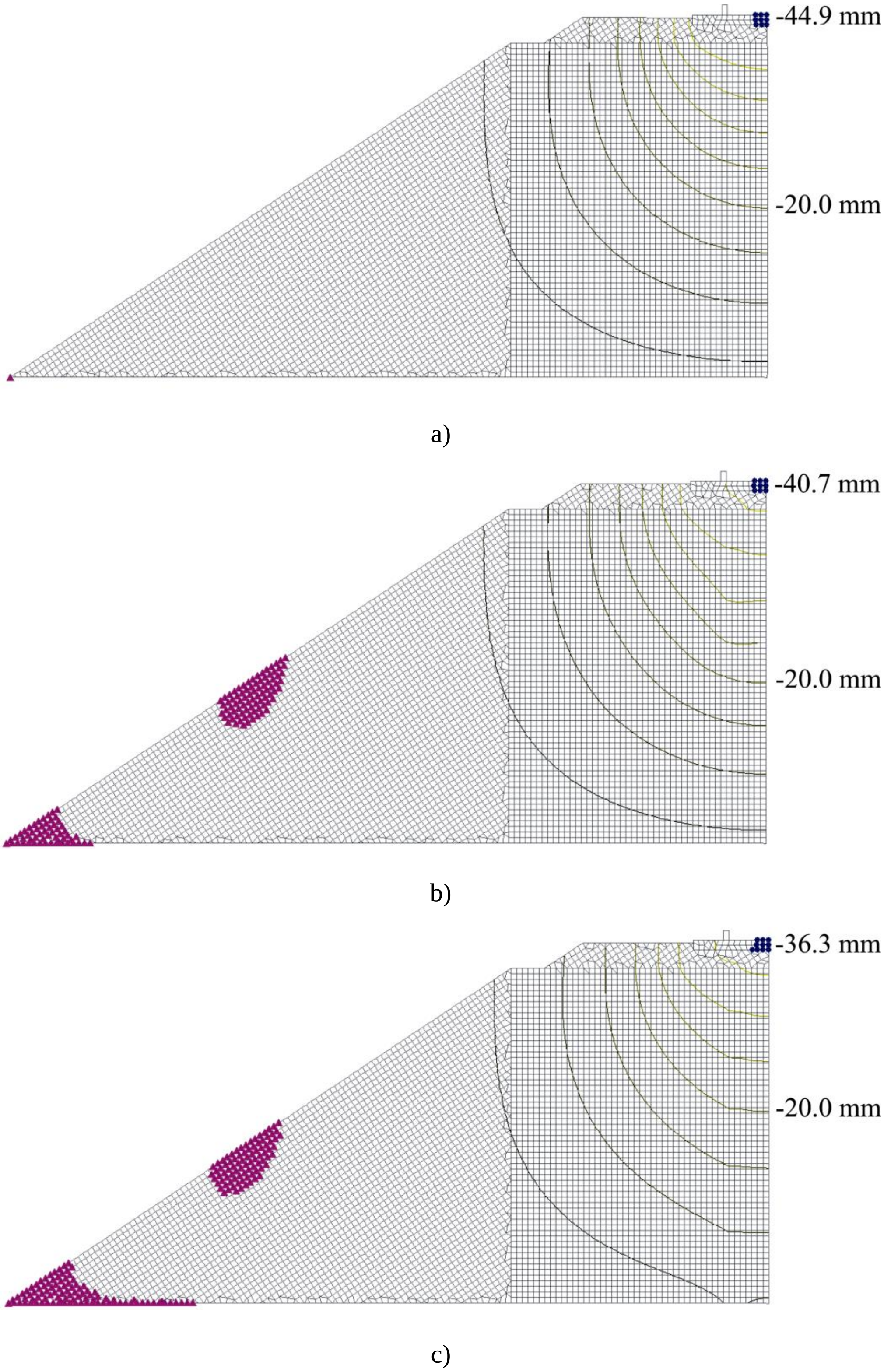


Figure 4. The strain state of the embankment (vertical displacements, mm; the step of the isolines is fixed and is 5.0 mm) with pile reinforcement with a length of a) 0 m (unreinforced); b) 2 m; c) 6 m.

The special display filter of the SCAD calculation complex is used to present the results of the strain state. With its help, horizontal and vertical displacements are represented for all strengthening options, and for each of them, a constant step of the deformation component is selected (2.0 mm for horizontal displacements and 5.0 mm for vertical displacements). This presentation, in addition to quantitative analysis, also allows for qualitative analysis, since the isolines in figures 3 and 4 have the same value. For convenience, two regions are shown in each of the pictures of the strain state: 1) the maximum value; and 2) the characteristic strain isoline (-4.0 mm for horizontal displacements and -20.0 mm for vertical displacements).

Even a qualitative analysis of the obtained results proves that the introduction of vertical elements with increased deformation properties into the soil environment (the elasticity modulus or deformation of pile or micropile material) is an effective method of reducing the strain state (figure 4). It should also be noted that the vertical component of deformation is significantly affected by strengthening with such elements, however, the special installation of the pile relative to the sleeper has a positive effect on the horizontal component as well, which is proven by the obtained results (figure 3).

There is no doubt that the introduction of the pile changes the character of the isolines. Unlike the unreinforced embankment (figures 3a and 4a), they lose evenness and smoothness. The presence of an element whose elasticity modulus is 5.6 times greater than the elasticity modulus of a clay loam forms a new picture of deformation. Thus, the core of the maximum horizontal displacements decreases, and the characteristic isoline (-4.0 mm) rises along the slope (figure 3b) to close inside the embankment (figure 3c). This is explained by the fact that the vertical element prevents horizontal deformations as well.

The maximum qualitative effect is observed in the case of vertical displacements (figure 4). The vertical element even with a length of 2 m significantly affects the distribution of isolines (figure 4b), and for a length of 6 m, it is cardinal. These changes can be traced on the example of a characteristic isoline (-20.0 mm for vertical displacements), rising upward towards the ballast.

Quantitative analysis of the maximum displacements made it possible to construct regularities of displacements and approximate them (figure 5).

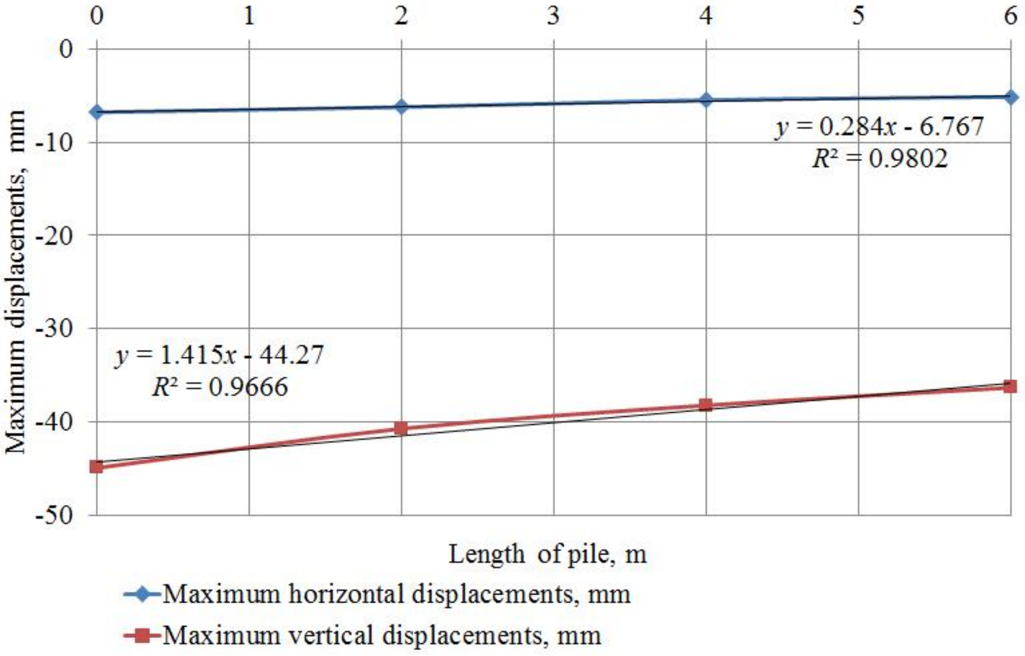


Figure 5. Regularities of changes in the vertical and horizontal displacements of the embankment when varying the vertical element length of strengthening.

The graph (figure 5) shows that the regularities of changes in the embankment displacement when varying the vertical element length of strengthening are linear (the correlation coefficient is R^2=0.97 ... 0.98). An important conclusion is that the increase in the vertical element length of strengthening provides a reduction in displacements by 1.1 ... 1.2 times. This can be the basis for an initial decision to choose the vertical element length of strengthening, based on economic conditions and the planned level of displacement reduction.

4. Conclusions

The article performed a numerical analysis of the finite-element model of the embankment, its soil base, the rail-sleeper grid, as well as the vertical element of strengthening with lengths of 2.0, 4.0, and 6.0 m. As an option for comparing the analysis results, an unreinforced version of the embankment has been calculated.

The results of the numerical analysis have been obtained allowing us to analyze the values of horizontal and vertical displacements. The results of the analysis prove that strengthening with such elements has a maximally positive effect on both components of deformation. It has been proven that the presence of vertical piles reduces the horizontal component of displacements by 1.1 ... 1.32 times, and the vertical component – by 1.1 ... 1.24 times.

Acknowledgments

The investigation results detailed in this paper were conducted with support from a grant provided by The National Research Foundation of Ukraine under the project "Scientific Justification of the Introduction of the European Track on the Territory of Ukraine in the Post-War Period" (project registration number 2022.01/0021), which was obtained through the "Science for the Recovery of Ukraine in the War and Post-War Periods" competition.

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