Determining Minimized Arrangement of Micro piles to stabilize High Railway Embankments on Loose Foundations

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Abstract

Construction of railway embankments on loose beds without using any methods of soil improvement (e.g. stone columns in silt and clay beds, deep soil mixing method, jet grouting and also using micropiles individually or in groups form) leads to reduction of embankment slope, which significantly increases the volume of soil operation.

Generally, micropile as a reinforcing element with the main characteristics of improving the mechanical-physical properties of soil, is a proper methodology for the aim of improving loose earth with low bearing capacity and intensive settlement characteristics.

This paper explores numerical models of not-reinforced and reinforced railway embankments (with the height of 10 to 25 m) rested on loose beds that simulated and analysed by SLIDE v. 5. It should be considered that in order to reinforce the embankments different arrangements of micropiles were used. In addition, the not-reinforced and reinforced embankments were analyzed against different load combinations that consist of railway operational load, permanent weight of the rail line and intense earthquake load. It should be mentioned that LM71 standard load was used as operational load during the simulations.

The main purpose of this paper is finding the optimum arrangement of micropiles to reinforce the high railway embankments on loose beds. Therefore, according to the numerical analyses procedure, it was resulted that the use of micropiles exactly between toe and 1/3 to 1/2 length of the embankment slope is the optimal way to reinforce the embankments on loose beds.

Keywords: Reinforcing element, micropiles, embankments, loose beds, numerical models.

1. Introduction

Generally, geotechnical engineers are facing two options in dealing with problematic soils such as loose soils with low bearing capacity or high consolidation, liquefied soils, remoulded soils, and so on:

- Use of load bearing elements in the soil to transfer the applied loads to a deeper, more competent or stable stratum; and
- Improvement and modification of physical and mechanical properties of soil mass.

Each of these solutions has its own specifications, which have been greatly developed over many years. Some of the innovative techniques have a nature combined of both methods (with the advantages of both), among which the use of micropiles individually or reticulated (in groups form) can be noted (Khayyer 2010).

Micropiles refer to the lightly reinforced and grouted piles with a diameter smaller than 30 cm. Micropile not only acts as a load bearing element resistant against applied loads, but also improves the mechanical properties of the surrounding soil because of the cement grouting (FHWA 2000).

Before using micropile as a way to reinforce the high embankments in the site conditions, the numerical and experimental investigations are necessary to prove the efficiency of this method. Accordingly, several numerical studies have been conducted by engineers' community during the recent years that express the applicability of micropiles in this way. For instance, Cantoni and Collotta (1989) investigated the reticulated micropiles structures to reinforce the slopes against sliding. Dam stabilization with micropiles was studied by Haider et al. (2004). In another work, Bruce et al. (2004) designed a micropile wall to stabilize a railway embankment by Flac-2D code. In addition, Wang et al. (2009) analyzed micropile foundation in subgrade by using finite element method. Finally, Howe (2010) examined the efficiency of micropiles for slope stabilization by using finite element and equilibrium point software.

Given the above, there is no comprehensive study on efficiency of micropiles to reinforce the high embankments on loose beds, so this paper is prepared to numerically examine the mentioned method of embankment strengthening in a software environment. It is remarkable that the study is about the embankment with height of 10 to 25 m.

It is noteworthy that in this paper, SLIDE version 5.0 was used to design micropiles for reinforcing embankment slope against the sliding. By using this 2D slope stability analysis software can calculate the safety factors for circular slope failure surfaces, based on a number of widely used limit equilibrium techniques including Bishop Method. In addition, some specifications are considered to select this software, which are as follows: combination of an attractive, easy to use CAD based graphical interface with a wide range of modelling and data interpretation options, the similarity between the simulated environment and real conditions, simplicity of the software environment, high capability of modelling the embankment and micropiles (Azami et al. 2003).
The main purpose of this design is to determine the most appropriate location of micropile embankment slope in order to be used in experimental modeling. The most critical material and geometric conditions for the embankment were considered to increase the efficiency of this investigation. Considering this issue and the realistic conditions established for the embankments, the following were considered for the intended simulation: the dead load resulting from weight of the rail line pavement, the live load resulting from the operational loads of rail line, and finally the earthquake load for earthquake-prone areas (Ehteshami et al. 2004).

2. Setup of the numerical simulations

As mentioned before, to examine the efficiency of micropiles to reinforce the embankments and determine the optimum arrangement of them, the numerical models of not-reinforced and reinforced embankments simulated by SLIDE that the significant analysis information are given in Table 1. It is to be noted that SLIDE is a 2D slope stability program for evaluating the stability of circular or non-circular failure surfaces in soil or rock slopes. SLIDE is very simple to use, and yet complex models can be created and analyzed quickly and easily. External loading, groundwater and support can all be modelled in a variety of ways (Azami et al. 2003).

Table 1. Analysis information of SLIDE

Analysis Method	Number of slices	Tolerance	Maximum number of iterations	Surface Type	Radius increment
Bishop simplified	25	0.005	50	Circular	10

It should be mentioned that in order to determine the optimum number of slices for embankment modelling process, this parameter was increased until no considerable difference was shown in the safety factor of slope stability. For example, increasing the number of slices from 6 to 25 did make a difference in the safety factor of 0.014. Increasing the number of slices beyond the number of 25, however, had very little effect.

2.1. Determining the properties of bed and embankment

2.1.1. The dimensions of bed and embankment

Considering the prevalent use of high embankments for making the infrastructure of railway lines, moreover the stability problems of them against the static and dynamic loads cause that the range of embankments height selected between 10 to 25 m for SLIDE simulations. It is to be noted that the bed dimensions determined proportional to the embankment dimensions (Table 2).

Table 2. The dimensions of bed and embankment

H (m)	L_S (m)	L_B (m)	W (m)	D_B (m)	D_{MB} (m)
15	27	15	6	15	2
20	36	20	6	20	2

According to UIC719-R code (1994), the embankment slope is typically considered to be 1 to 3, 1 to 2 and 2 to 3. Obviously, if the slope increases, the volume of the soil operation in the construction of embankment is reduced. Consequently, because of the use of micropile for creating economic balance, maximum slope was considered in the simulation of embankment. In order to optimize the paper size just shown the figures of embankments with the height of 15 and 20 m, as the pictorial outputs of SLIDE analyses (Figures 1 and 2).

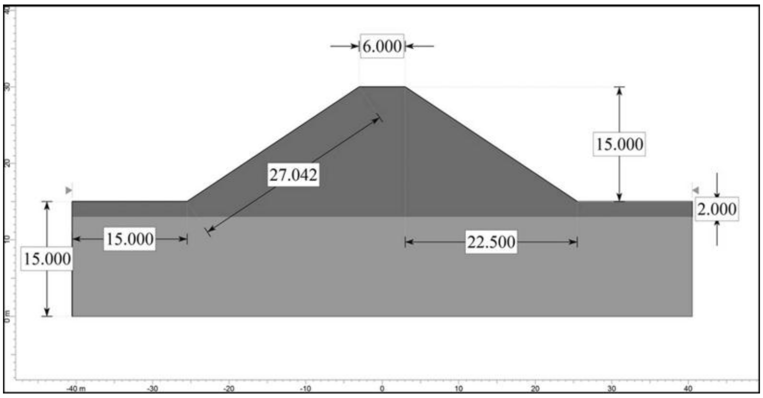

Figure 1: Dimensions of the 15-m embankment simulated by SLIDE

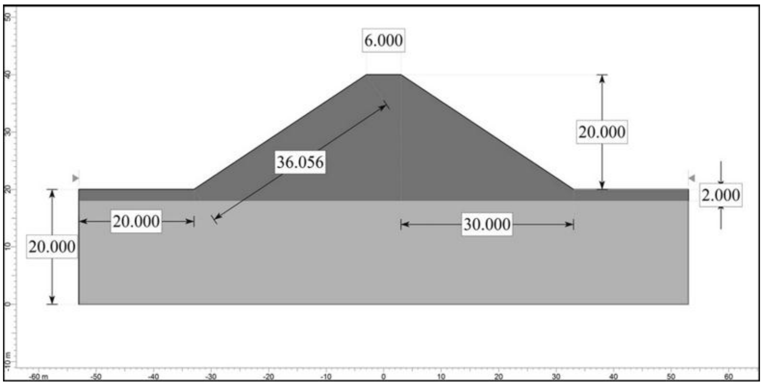

Figure 2. Dimensions of the 20-m embankment simulated by SLIDE

2.1.2. The material properties of bed and embankment

Given that the most critical conditions were considered, the soil of bed was chosen from loose soils with low bearing capacity. Accordingly, the bed material was selected from the SP soil (Das 2005). Also to model the embankment and a upper 2-m layer of the bed, the properties of SC soil were used (according to the soil characteristics of the implemented embankments in the Iranian railways after 1978) (Zakeri, Shahroudi 2006). The selected material properties are given in Table 3.

Table 3. The material properties of bed and embankment

Properties / Type of soil	Strength Type	γ_S (kN/m^3)	c (kPa)	φ (degree)
Embankment soil	Mohr-Coulomb	20	20	30
Bed soil	Mohr-Coulomb	18	1	28

2.2. Loading the embankment

The vertical loads that were assumed to simulate the embankment in SLIDE are based on permanent weight of rail line and railway operational load; moreover, it should be considered that operational load was calculated based on Load Model 71. LM 71 represents the static effect of vertical loading due to normal rail traffic. The characteristic values given in Figure 3 shall be multiplied by a factor α, on lines carrying rail traffic which is heavier or lighter than normal rail traffic. This factor shall be one of the following:

α = {0.75, 0.83, 0.91, 1.00, 1.10, 1.21, 1.33, 1.46}.

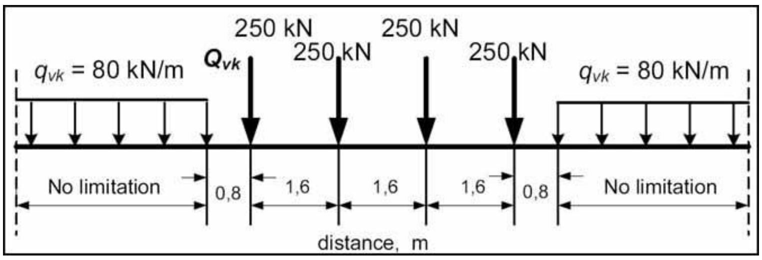

Figure 3. Load Model 71 and characteristic values for vertical loads (EN 1991-2 2003)

The value 1.33 is normally recommended on lines for freight traffic and international lines.

The vertical loads are calculated according to Eq. (1) (EN 1991-2 2003).

$$Q = P / (L \times W) \quad (1)$$

$$Q_{D1} = (T_B.\ W_B.\ L.\ \gamma_B) / (L.W) = (0.3 \times 3.65 \times 1 \times 1.9) / (1 \times 6) = 0.347\ (t.m/m^2)$$

$$Q_{D2} = (T_{S\text{-}b.}\ W_{S\text{-}b}.\ L.\ \gamma_{S\text{-}b}) / (L.W) = (0.15 \times 6 \times 1 \times 1.9) / (1 \times 6) = 0.285\ (t.m/m^2)$$

$$Q_L = (4 \times \alpha.Q_{vk}) / (L.W) = (4 \times 1.33 \times 25) / (6.4 \times 6) = 3.46\ (t.m/m^2)$$

The effect of impact load is applied for vertical loads by using the Eq. (2), (3), (4) and (5) (Ehteshami et al. 2004).

$$\delta = 1 + \alpha' + \beta + \gamma \quad (2)$$

$$\alpha = 0.04\ [V/100]^2 \quad (3)$$

$$\beta = 0.2$$

$$\gamma = \gamma^0\ .\ \alpha'\ .\ \beta \quad (4)$$

$$\gamma^0 = 0.1 + 0.17 \times [V/100]^2 \quad (5)$$

$$V{=}200\ (Km/h) \rightarrow \delta = 1 + 0.16 + 0.2 + 0.025 = 1.385 > 1.3$$

It should be mentioned that to apply the earthquake load, a seismic load coefficient (horizontal) was assumed to be equal to 0.3.
Finally, the values of load combinations to simulate the embankment by SLIDE are calculated according to the Eq. (6), (7) and (8).

$$\text{Load combination Case 1} = \delta\ (Q_{D1} + Q_{D2}) = 0.875\ (t.m/m^2) \quad (6)$$

$$\text{Load combination Case 2} = \delta\ (Q_L + Q_{D1} + Q_{D2}) = 5.667\ (t.m/m^2) \quad (7)$$

$$\text{Load combination Case 3} = Q_E + \delta\ (Q_{D1} + Q_{D2}) \quad (8)$$

It is to be noted that according to UIC719-R code (1994), the allowable safety factors of embankment slope stability for load combinations Case 1, 2 and 3 are 1.5, 1.3 and 1.1, respectively.

2.3. Determining the properties of micropiles

2.3.1. The material properties of micropiles

Water-cement ratio and the characteristics of reinforcing steel can be considered as the most important material properties of micropiles. According to FHWA guidelines (2000), water-cement ratio was considered between 0.45 to 0.6. In addition, the elasticity modulus of cement grout and reinforcing steel (for steel bar and casing pipe) were assumed to be equal to 31 and 200 Gpa (standard wrought steel), respectively (Table 4).

Table 4. The material properties of micropiles

E_G (MPa)	f'_c (MPa)	W/C	E_S (MPa)
31000	34.5	0.45 to 0.6	200000

Recent research suggests, however, that in certain conditions and for certain micropile arrangements, the micropiles are principally, directly, and locally subjected to bending and shearing forces, specifically near the sliding surface (Pearlman et al. 1992). So, according to the assumptions of SLIDE code to model the micropiles, amount of allowable shear strength of micropile is used that it was considered to be $0.55 \times \sqrt{f'c} \times \pi R2$ during the simulation, where f′c is the compressive strength of the cement grout. In addition, an equivalent steel section of micropiles was used (Eq. (9)) to calculate the shear strength according to the Eq. (10) (Figure 4) (ACI 318 2005).

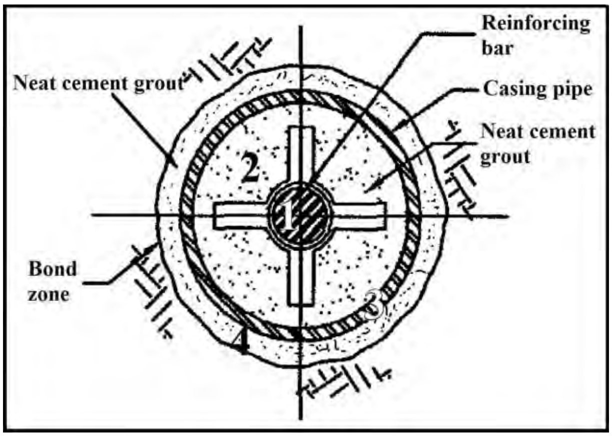

Figure 4. Cross-section of the micropile with a diameter of 30 cm

$$E_S I_1 + E_G I_2 + E_S I_3 + E_G I_4 = E_G I \quad (9)$$

$$200 \times 5.15 + 31 \times 31038.04 + 200 \times 8717.59 + 31 \times 267035.38 = 31 \times (\pi R^4 / 4)$$

$$\rightarrow R = 25.92 \text{ (cm)}$$

$$F_S = 0.55 \times \sqrt{f'_c} \times \pi R^2 \quad (10)$$

$$F_S = 0.55 \times \sqrt{34500} \times 0.211 = 21.555 \text{ (KN)}$$

2.3.2. The geometric parameters of micropiles

Determining the geometric parameters of micropiles is important to simulate reinforced embankment which were assumed as Table 5 (Figure 5).

- Length of micropiles: to reduce the operation of trial and error method in order to obtain optimum arrangement of micropiles, constant values were considered for the length of micropiles, which assumed to be 10 to 25 m for the 10 to 25-m embankments, respectively;
- Angle of micropiles to the vertical axis: the angle of micropiles was selected between 0 to 30 degrees to the vertical axis. According to the deep failure of embankment slope and the selected length of micropiles, the angles were selected such a way that the micropiles cross the sliding surface certainly;
- Diameter of micropiles: to reduce the number of micropiles for savings in financial costs of construction process, the diameter was considered to be the maximum dimension, equal to 30 cm;
- Number of micropiles: total number of micropiles increased as trial and error until achieving the allowable safety factor of slope stability; and
- Micropiles spacing: it was also reduced as trial and error until achieving the allowable safety factor of slope stability. It should be considered that this item was variable in two orientations, lateral and longitudinal spacing that the first is the distance between distributed micropiles along the length of the slope, and the second is the distance between micropiles along the length of embankment (FHWA 2000).

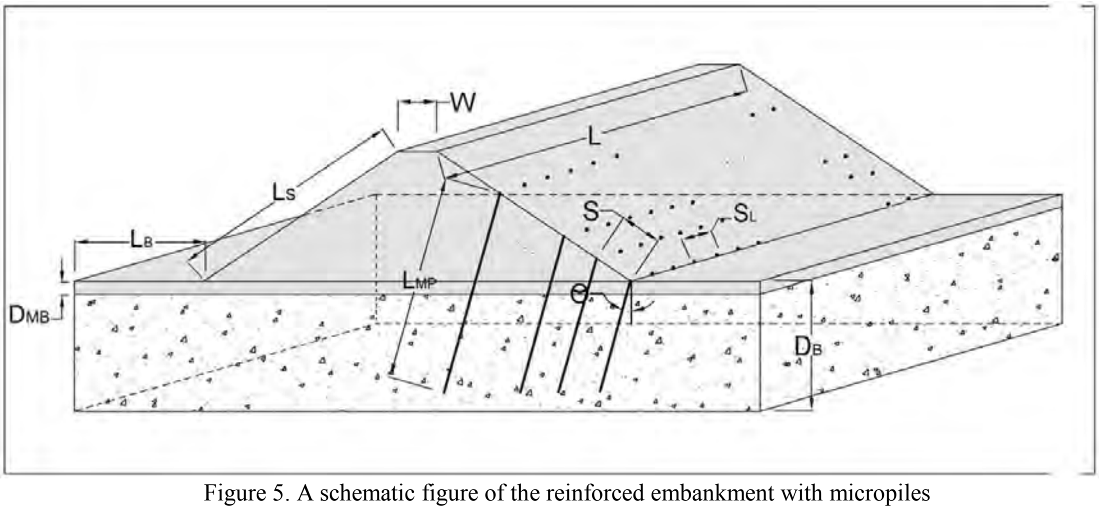

Figure 5. A schematic figure of the reinforced embankment with micropiles

Table 5. The geometric parameters of micropiles arrangement (refer to Figure 5 and 6)

Parameters / Arrangement number	L_{MP} (m)	θ (degree)	D_{MP} (cm)	N_S	S (m)	S_L (m)
No. 1 (based on Case A in Figure 6)	15	0, 10, 20, 30	30	4	0 (embankment toe)	0.5
No. 2 (based on Case B in Figure 6)	15	0	30	4	6.75	0.5
No. 3 (based on Case B in Figure 6)	15, 18.33, 21.66, 25	0	30	4	6.75	0.5
No. 4 (based on Case B in Figure 6)	15	0	30	3	4.5	1
No. 5 (based on Case B in Figure 6)	15	0	30	3	4.5	0.5
No. 6 (based on Case B in Figure 6)	15	0	30	4	3	0.5
No. 7 (based on Case B in Figure 6)	15	15	30	4	3	0.5
No. 8 (based on Case A in Figure 6)	20	0, 6, 12, 18, 24, 30	30	6	0 (embankment toe)	0.5
No. 9 (based on Case B in Figure 6)	20	0	30	6	6	0.5
No. 10 (based on Case B in Figure 6)	20, 23.33, 26.66, 30	0	30	6	6	0.5
No. 11 (based on Case B in Figure 6)	20	0	30	5	4.5	1
No. 12 (based on Case B in Figure 6)	20	0	30	5	4.5	0.5
No. 13 (based on Case B in Figure 6)	20	0	30	6	3.6	0.5
No. 14 (based on Case B in Figure 6)	20	15	30	6	3.6	0.5

It is to be noted that by using the recommendations of UIC719-R code (1994) about the location of micropiles in the embankment slope can reduce the steps of designing in trial and error method. Accordingly, in this paper all the micropiles arrangements were based on the both recommended case of UIC719-R code (1994) (Figure 6).

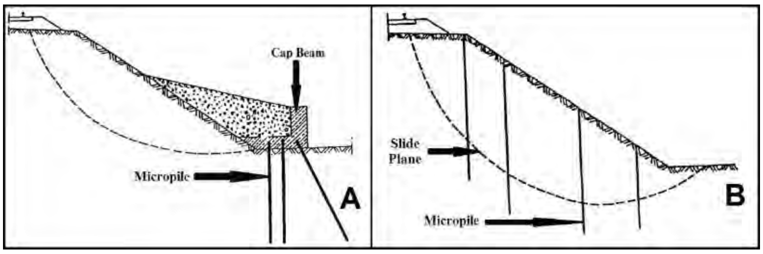

Figure 6. Recommendations of UIC719-R code (1994) on the location of micropiles in the embankment slope

3. Results and Discussion

First, the embankment stability was examined in a not-reinforced condition, then it would be reinforced with different arrangement of micropiles; and the analyses procedure continued as a trial and error method, until achieving the allowable safety factor of slope stability.

3.1. Analyses results of the not-reinforced embankments

Results of the analyses procedure on not-reinforced embankments with the height of 10 to 25 m are as follows:

1. As was expected, the load combination Case 3 was more critical than the load combinations Case 1 and 2, the reasons for which are as follows :
   - Lateral loads like earthquake load are more effective for creating sliding on the embankments slope; and
   - Lateral loads are more effective on the high embankments.
2. The embankments was not even close to the moment of failure against the load combinations Case 1 and 2 (Figures 6(a) and 7(a)), while deep sliding occurred in the embankments slope against the load combination Case 3 (Figures 6(b) and 7(b)); and

3. The main reason of deep sliding in the embankments slope was the lateral movement of loose layers in the beds (Figures 7 and 8).

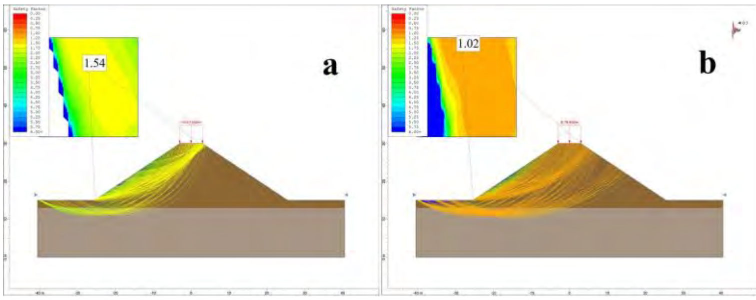

Figure 7. (a) The stability of not-reinforced embankment with the height of 15 m against the load combination Case 2 (FS = 1.54 > 1. 3), and (b) its failure against the load combination Case 3 (FS = 1.02 < 1. 1)

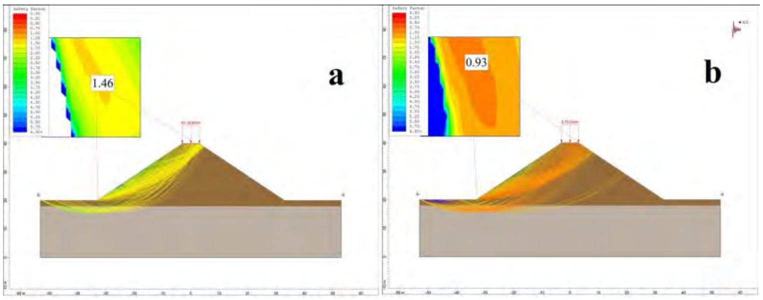

Figure 8. (a) The stability of not-reinforced embankment with the height of 20 m against the load combination Case 2 (FS = 1. 46 >1. 3), and (b) its failure against the load combination Case 3 (FS = 0. 93 < 1. 1)

According to the Figures 6 and 7, the embankments failure just appeared against the load combination Case 3. Accordingly, all the followed numerical models were simulated and analyzed against the above load combination.

3.2. Analyses results of the embankments reinforced with micropiles

To examine the efficiency of micropiles to reinforce the high embankments, 10 to 25-m embankments, which were reinforced with different arrangements of micropiles, were studied; and the analyses results are given in Table 6.

Table 6. The results of analyses procedure for the reinforced embankments

	15-m embankment							20-m embankment						
No. of micropiles arrangement	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 12	No. 13	No. 14
Safety factor	1.02	1.09	1.10	1.05	1.08	1.10	1.10	0.93	1.10	1.10	1.00	1.08	1.10	1.10

Results of the numerical analyses on embankments with height of 10 to 17 m:

1. Using the micropiles exactly in the toe of embankments slope was not very effective in order to prevent the sliding due to the high altitude of embankments; and failure still occurred in the upper part of the embankments.
2. The distribution of micropiles along the whole length of embankments slope was effective only by using the micropiles with very long and non-standard length in order to cross the sliding surface.
3. The micropiles distribution between the toe and 1/3 length of the above embankments slope was the most effective and appropriate location to reinforce the embankments.

Results of the numerical analyses on embankments with height of 17 to 25 m:

1. Using the micropiles exactly in the toe of the above embankments slope even with long length could not stabilize the slope.
2. The distribution of micropiles along the whole length of the above embankments slope was effective only by using the micropiles with very long and non-standard length in order to cross the sliding surface.
3. The micropiles distribution between the toe and 1/2 length of the above embankments slope was the most effective and appropriate location to reinforce the embankments.

According to the analyses results, it is observed that the optimum arrangements of micropiles to reinforce the embankments with the height of 15 and 20 m are arrangements No. 6 and 13, respectively (Figures 9 and 10).

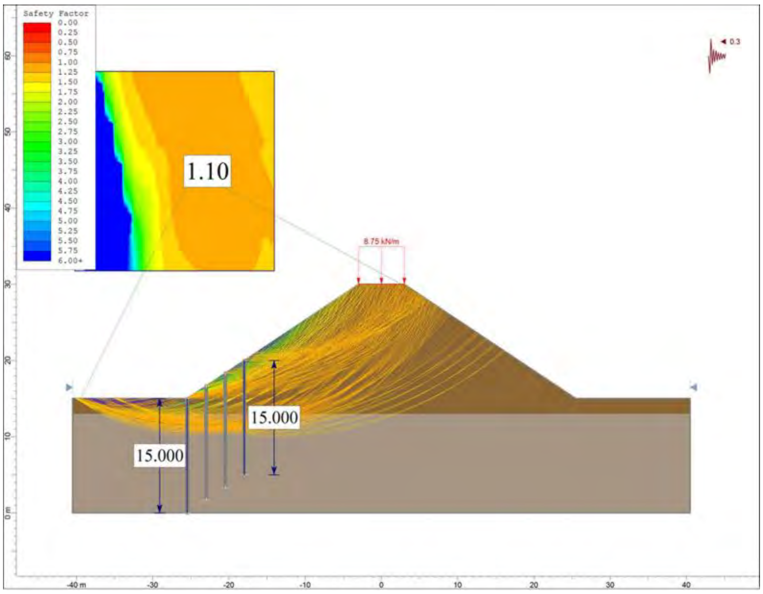

Figure 9. Results of the analysis procedure on 15-m embankment reinforced with micropiles arrangement No. 6 (FS = 1. 1)

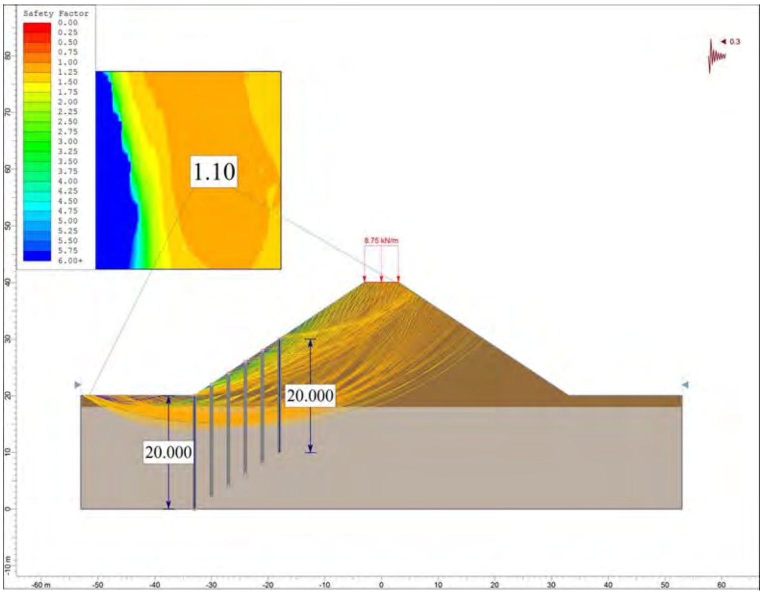

Figure 10. Results of the analysis procedure on 20-m embankment reinforced with micropiles arrangement No. 13 (FS = 1. 1)

4. Conclusion

In this paper, high railway embankments which are rested on loose beds, were simulated and analyzed against the standard load combinations in SLIDE to determine the optimum arrangement of micropiles.

To this end, in the first step, not-reinforced embankments with height of 15 to 25 m rested on loose beds were simulated in order to investigate the slope stability, then the embankments reinforced with different arrangements of micropiles to examine the efficiency of this methodology. Finally, the optimum arrangement of micropiles was determined.

Based on the research, it was resulted that the best location of micropiles to reinforce the high railway embankments is between the toe and middle of embankments slope; moreover, by using the maximum diameter of micropiles can reduce the number of them to minimize the financial costs of construction process. It should be considered that the optimum arrangement of micropiles was determined in a trial and error method, and to reduce the steps of this method can assume the amounts of some geometric parameters such as length and angle, constantly. Finally, the amounts of other parameters obtained during the analyses procedure.

Based on the results obtained, the use of micropiles exactly between the toe and 1/3 to 1/2 length of embankments slope is the optimal way to reinforce the embankments on loose beds by modifying the physical and mechanical properties of beds soil, sewing their loose layers together, and transferring the applied loads to deeper, more competent or stable stratums.

List of Symbols

c	Cohesion of soil (kpa);
D_B	Depth of the bed (cm);

D_{MB}	Depth of the modified part of the bed (cm);
D_{MP}	Micropile diameter (cm);
E_G	Elasticity modulus of cement grout (Gpa);
E_S	Elasticity modulus of reinforcing steel (Gpa);
F_S	Shear strength (KN);
f'_c	Compressive strength of the cement grout (Mpa);
H	Height of the embankment (m);
I	Moment of inertia of the equivalent steel section (cm^4);
I_1	Moment of inertia of area 1 (cm^4);
I_2	Moment of inertia of area 2 (cm^4);
I_3	Moment of inertia of area 3 (cm^4);
I_4	Moment of inertia of area 4 (cm^4);
L	Length of loading area (m);
L_B	Length of the bed side (m);
L_S	Length of the slope (m);
L_{MP}	Micropile length (m);
N	Number of micropiles;
N_S	Number of micropiles in embankment section;
P	Different loads of the rail line (t.m) ;
Q	Applied distributed constant load on the embankment crest (orientation: vertical) ($t.m/m^2$);
Q_{D1}	Overhead of the ballast weight ($t.m/m^2$);
Q_{D2}	Overhead of the sub-ballast weight ($t.m/m^2$);
Q_E	Earthquake load;
Q_L	Distributed operational load ($t.m/m^2$);
Q_{vk}	Traffic load in Load Model 71 ($t.m/m^2$);
R	Radius of the equivalent steel section(cm);
S	Lateral micropile spacing (transverse distance between micropiles) (m);
S_L	Longitudinal micropile spacing (m);
T_B	Thickness of ballast (m);
T_{S-b}	Thickness of sub-ballast (m);
V	Velocity (Km/h);
W	Width of embankment crest (m);
W_B	Width of ballast (m);
W_{S-b}	Width of sub-ballast (m);
W/C	Water cement ratio

Greek symbols

α	A factor that shows the traffic volume on the rail lines;
β, γ , α'	Velocity factors (non-dimensional);
δ	Impact factor (non-dimensional);
φ	Angle of internal friction (degree);
γ_B	Density of ballast gravel (kN/m^2);
γ_S	Soil density (kN/m^2);
γ_{S-b}	Density of sub-ballast gravel (kN/m^2); and
θ	Angle of micropile to the vertical axis (degree).

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