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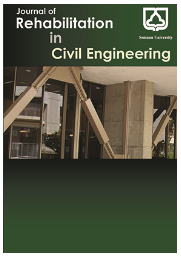

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Static and Dynamic Analyses of Micropiles to Reinforce the High Railway Embankments on Loose Beds

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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 gradient, 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 non-reinforced and reinforced railway embankments (with the height of 10 to 25 m) rested on loose beds that simulated and analyzed by SLIDE software. It should be considered that in order to reinforce the embankments using different arrangements of micropiles. In addition, the non-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 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.

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:

A. Use of load bearing elements in the soil to transfer the applied loads to a deeper, more competent or stable stratum;

B. 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 [1].

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 [2].

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 [3] investigated the reticulated micropiles structures to reinforce the slopes against sliding. Dam stabilization with micropiles was studied by Haider et al. [4]. In another work, Bruce et al. [5] designed a micropile wall to stabilize a railway embankment in the environment of Flac-2D software. In addition, Wang et al. [6] analyzed micropile foundation in subgrade by using finite element method. Finally, Howe [7] examined the efficiency of micropiles for slope stabilization by using finite element and equilibrium point software.

Accordance with the above, this paper is prepared to numerically examine the micropiles in a software environment, too. 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 has been 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, micropiles against the applied loads [8].

The main purpose of this design is to determine the most appropriate location of micropile embankment slope in order to be used in experimental modelling. The most critical material and geometrical conditions for the embankment have been considered to increase the efficiency of this investigation. Considering this issue and the realistic conditions established for this embankment, the following have been 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 (that's calculated based on LM71 standard load), and finally the earthquake load for earthquake-prone areas [9].

2. Inputs of SLIDE Software for Designing Micropiles

As mentioned before, to examine the efficiency of micropiles to reinforce the embankments and determine the optimum arrangement of them, the numerical models of non-reinforced and reinforced embankments simulated by SLIDE software that the significant analysis information are given in Table 1. It's 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.

Table 1. Analysis information of SLIDE software

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

2.1. Determining the properties 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 for SLIDE simulations. It's to be noted that the bed dimensions determined based on a logical relative to the embankment dimensions (Table 2).

According to UIC719-R code [10], the gradient of embankment slope is typically considered to be 1 to 3, 1 to 2 and 2 to 3. Obviously, if the slope gradient 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 gradient has been 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 (Figs 1 and 2).

Table 2. The dimensions of bed and embankment

Height of the embankment (m)	Length of the embankment slope (m)	Length of the bed sides (m)	Length of the embankment crest (m)	Depth of bed (m)	Depth of the modified part of the bed (m)
15	27	15	6	15	2
20	36	20	6	20	2

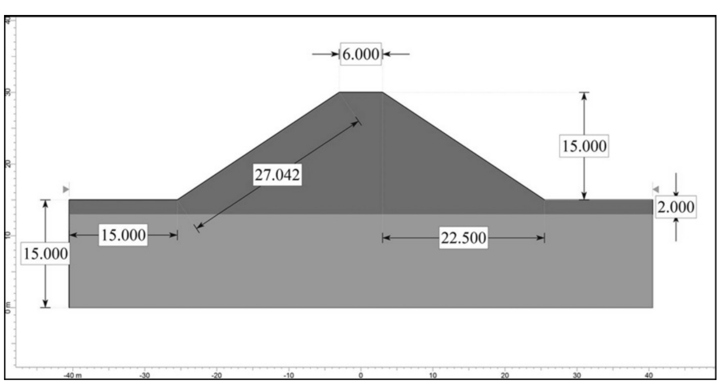

Fig 1. Dimensions of a 15-m embankment simulated by SLIDE software

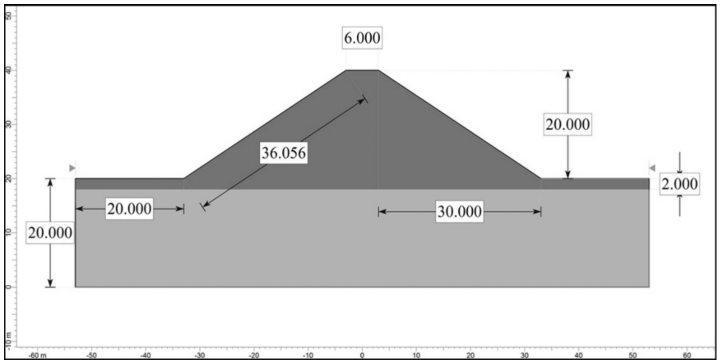

Fig 2. Dimensions of a 20-m embankment simulated by SLIDE software

Given that the most critical conditions have been considered, the soil of bed was chosen from loose soils with low bearing capacity. Accordingly, the bed material was selected from the SP sand [11]. Also to model the embankment and an upper 2-m layer of the bed, the properties of SC material were used (according to the soil characteristics of the implemented embankments in the Iranian railways after 1978) [12]. 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_{Soil} (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 the SLIDE environment are based on permanent weight of rail line and railway operational load. Also, to apply the earthquake load, a seismic load coefficient (horizontal) was assumed to be equal to 0.3 . It's to be noted that the unit weight of ballast has been supposed to be 1.9 t/m^3. The vertical overheads are calculated according to Eq. (1).

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

$$Q_L = (4\times37.5) / (6.4\times6) = 3.91 \text{ (t.m/m}^2)$$

$$Q_{D1} = (0.3\times1.9\times3.65) / 6 = 0.347 \text{ (t.m/m}^2)$$

$$Q_{D2} = (0.15\times1.9\times6) / 6 = 0.285 \text{ (t.m/m}^2)$$

It is noteworthy that the amount of operational load determined depending on the amount of axial force which is variable between 20 to 37.5 ton. Furthermore, the effect of impact load is applied for vertical efforts by using the Eq. (2), (3), (4) and (5).

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

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

$$\beta = 0.2$$

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

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

V=200 (Km/h) → δ = 1+0.16+0.2+0.025 = 1.385 > 1.3

Finally, the values of load combinations to simulate the embankment by SLIDE, are calculated according to the Eq. (6), (7) and (8).

load combination Case 1 = $Q_{D1}+Q_{D2}+\delta.(Q_{D1} + Q_{D2}) = 0.632+0.243 = 0.875$ (t.m/m^2) (6)

load combination Case 2 = $Q_L+Q_{D1}+Q_{D2}+\delta.(Q_L+Q_{D1}+Q_{D2}) = 0.632+3.91+1.5 = 5.41$ (t.m/m^2) (7)

load combination Case 3 = $Q_E+Q_{D1}+Q_{D2}+\delta.(Q_{D1}+Q_{D2})$ (8)

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

2.3. Determining the properties of micropiles

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

Elasticity modulus of cement grout (MPa)	Compressive strength of cement grout (MPa)	Water cement ratio	Elasticity modulus of reinforcing wire (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 [13]. Accordingly, to simulate the micropiles in the environment of SLIDE software, the amount of allowable shear strength of micropile is used, that has been considered to be $0.55\times\sqrt{f'_c}\times\pi R^2$, 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 [14]).

$$E_{Steel}\, I_1 + E_{Grout}\, I_2 + E_{Steel}\, I_3 + E_{Grout}\, I_4 = E_{Grout}\, I \quad (9)$$

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

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

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

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

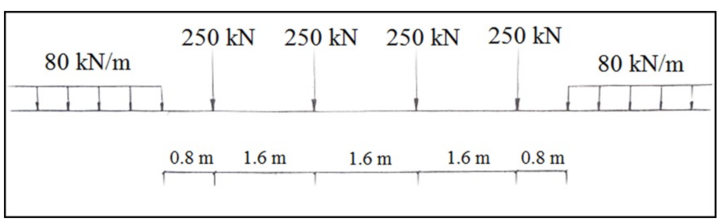

Fig 3. Representation of LM71 standard load (Ehteshami et al., 2004)

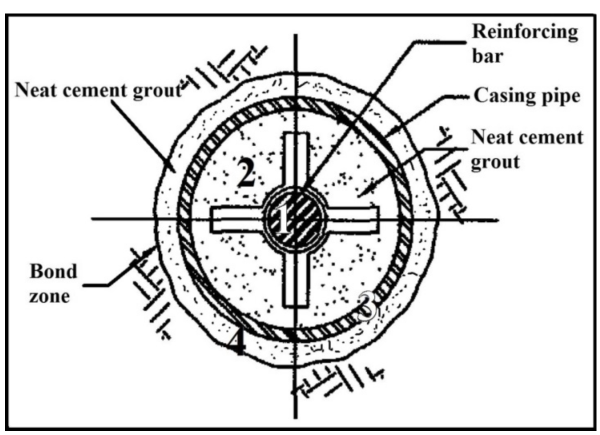

Fig 4. Cross-section of the micropile with a diameter of 15 cm

The geometrical parameters of micropiles

Determining the geometrical parameters of micropiles are important to simulate reinforced embankment which were assumed as Table 5.

A. Length of micropiles: to reduce the operation of trial and error method in order to obtain optimum arrangement of micropiles, constant values have been considered for the length of micropiles, which assumed to be 10 to 25 m for the 10 to 25-m embankments, respectively;

B. Angle of micropiles relative to the vertical axis: the angle of micropiles has been selected between 0 to 30 degree relative 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;

C. 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;

D. Number of micropiles: total number of micropiles increased as trial and error until achieving the allowable safety factor of embankment slope stability; and

E. Micropiles spacing: it was also reduced as trial and error until achieving the allowable safety factor of embankment 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 embankment slope, and the second is the distance between micropiles along the length of embankment (FHWA, 2000).

It's 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 5).

Table 5. The geometric parameters of micropiles arrangement

Parameters / Arrangement number	L_{MP} (m)	θ (degree)	D_{MP} (cm)	$N_{Section}$	$S_{Lateral}$ (m)	$S_{Longitudinal}$ (m)	Length of the slope that reinforced
No. 1	15	0 to 30	30	4	0	0.5	Toe of the embankment slope
No. 2	15	0	30	4	6.75	0.5	Whole the length
No. 3	15 to 25	0	30	4	6.75	0.5	Whole the length
No. 4	15	0	30	3	4.5	1	1/3length
No. 5	15	0	30	3	4.5	0.5	1/3length
No. 6	15	0	30	4	3	0.5	1/3length
No. 7	15	15	30	4	3	0.5	1/3length
No. 8	20	0 to 30	30	6	0	0.5	Toe of the embankment slope
No. 9	20	0	30	6	6	0.5	Whole the length
No. 10	20 to 30	0	30	6	6	0.5	Whole the length
No. 11	20	0	30	5	4.5	1	1/2length
No. 12	20	0	30	5	4.5	0.5	1/2length
No. 13	20	0	30	6	3.6	0.5	1/2length
No. 14	20	15	30	6	3.6	0.5	1/2 length

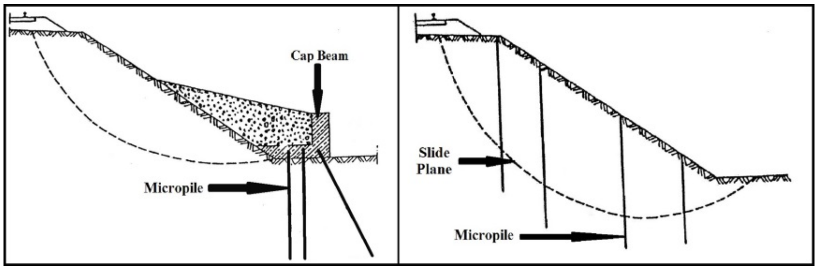

Fig 5. Recommendations of UIC719-R code (1994) about the location of micropiles in the embankment slope

3. Designing the micropiles to reinforce the high railway embankments on loose beds

First, the embankment stability was examined in a non-reinforced condition, then it would be reinforced with different arrangement of micropiles; and the analysis procedure continued as a trial and error method, until achieving the allowable safety factor of embankment slope stability.

3.1. Analysing the non-reinforced embankments

Results of the analysis procedure on non-reinforced embankments with the height of 10 to 25 m are as follows:

A. 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.

B. The embankments wasn't even close to the moment of failure against the load combinations Case 1 and 2 (Figures 6(a) and 7(a)), while deep sliding occurs in the embankments slope against the load combination Case 3 (Figures 6(b) and 7(b)); and

C. The main reason of deep sliding in the embankments slope was the lateral movement of layers of loose beds (Figures 6 and 7).

According to the Figures 6 and 7, the embankments failure just appeared against the load combination Case 3. Accordingly, all the followed numerical simulations would be done based on this load combination.

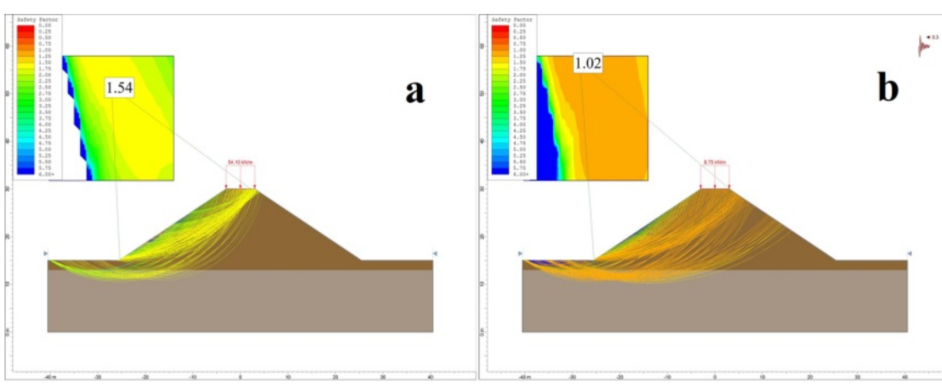

Fig 6. (a) The stability of non-reinforced embankment with the height of 15 m against the load combination Case 2 (FS = 1.54 > 1. 3), and (b) its failure against the load combination Case 3 (FS = 1.02 < 1. 1)

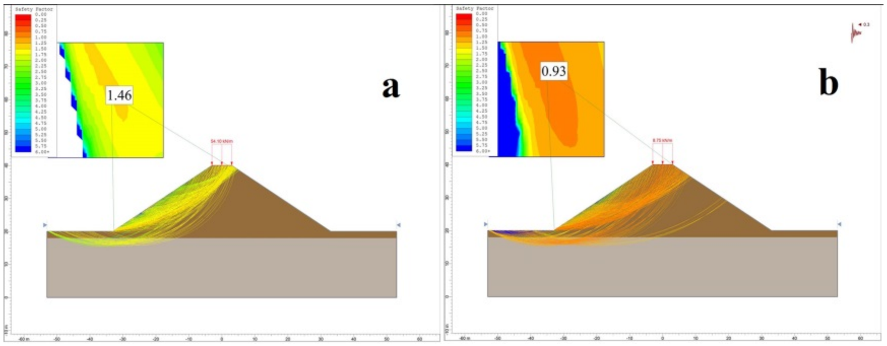

Fig 7. (a) The stability of non-reinforced embankment with the height of 20 m against the load combination Case 2 (FS = 1. 46 >1. 3), and (b) its failure against the load combination Case 3 (FS = 0. 93 < 1. 1)

3.2. Analysis of embankments reinforced with micropiles

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

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

A. Using the micropiles exactly in the toe of 10 to 17-m 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.
B. The distribution of micropiles along the whole length of slope for the embankments with the height of 10 to 17 m, was effective only by using the micropiles with very long and non-standard length in order to cross the sliding surface.
C. The micropiles distribution between the toe and 1/3 length of slope was the most effective and appropriate location to reinforce the slope of embankments with the height of 10 to 17 m.

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

A. Using the micropiles exactly in the toe of 17 to 25-m embankments slope even with long length couldn't stabilize the slope.
B. The distribution of micropiles along the whole length of slope for the embankments with the height of 17 to 25 m, was effective only by using the micropiles with very long and non-standard length in order to cross the sliding surface.
C. The micropiles distribution between the toe and 1/2 length of slope is the most effective and appropriate location to reinforce the slope of embankments with the height of 17 to 25 m.

According to the above mentioned, it's 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 (Figure 8 and 9).

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

Number 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	1.09	1.10	1	1.08	1.10	1.10

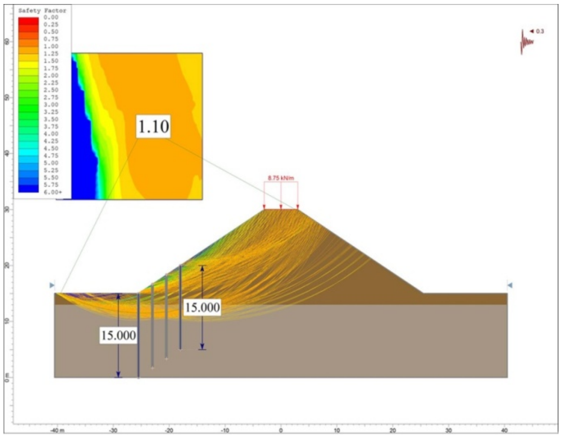

Fig 8. The results of analysis procedure on 15-m embankment reinforced with micropiles arrangement No. 6 (FS = 1. 1)

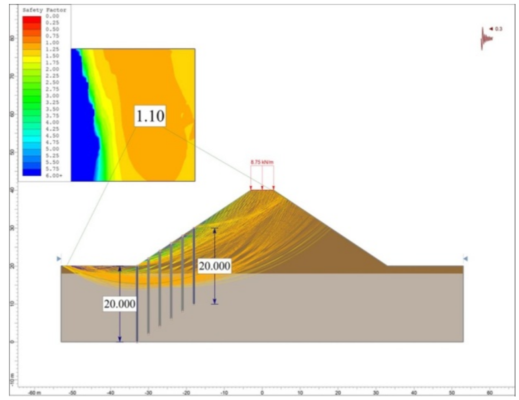

Fig. 9. The results of analysis procedure on 20-m embankment reinforced with micropiles arrangement No. 3 (FS = 1. 1)

4. Conclusion

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

To this end, in the first step, the non-reinforced high embankments 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 has been determined in a trial and error method, and to reduce the steps of this method can assume the amounts of some geometrical parameters such as length and angle, constantly. Finally, the amounts of other parameters obtained during the software analysis.

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

Notation

B: width of loading area (width of embankment crest) (m);

c: cohesion of soil (kpa);

D_{MP}: micropile diameter (cm);

E_{Grout}: elasticity modulus of cement grout (Gpa);

E_{Steel}: elasticity modulus of reinforcing steel (Gpa);

F_S: shear strength (KN);

f'_c: compressive strength of the cement grout (MPa);

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 (length of embankment crest) (m);

L_{MP}: micropile length (m);

N: number of micropiles;

$N_{Section}$: number of micropiles in embankment section;

P: operational load or permanent weight of rail line (t.m) ;

Q: applied distributed constant load on the embankment crest (orientation: vertical) ($t.m/m^2$);
Q_{D1}: ballast overhead ($t.m/m^2$);
Q_{D2}: sub-ballast overhead ($t.m/m^2$);
Q_E: earthquake load (seismic load coefficient = 0.3);
Q_L: distributed operational load (based on LM71 standard load Fig. 3.) ($t.m/m^2$);
R: radius of the equivalent steel section(cm);
$S_{Lateral}$: lateral micropile spacing (transverse distance between micropiles) (m);
$S_{Longitudinal}$: longitudinal micropile spacing (m);
V: velocity (Km/h);
α, β, γ : velocity factors (non-dimensional);
δ: impact factor (non-dimensional);
φ: angle of internal friction (degree);
γ_{Soil}: soil density (kN/m^2); and
θ: angle of micropile relative to the vertical axis (degree).

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