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Slope Stability and Reliability Analysis of Earth Embankment Constructed for the Doubling of Railway Track

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ABSTRACT Embankments of greater height pose threat to its stability and require geotechnical investigation and intervention. Conventionally, limit equilibrium approach is used to estimate the factor of safety of the slope to assess its stability. Over a period of time, with experience and engineering judgments, a factor of safety of 1.4 is deemed sufficient for Indian practice. In the approach, it is inherently assumed that different sources of uncertainty due to testing errors, model transformation, and inherent variability of the geo-material are taken care of with the use of single value of factor of safety. Still, a question remains, whether the suggested factor of safety is acceptable in a given environment of uncertainty or there is a need to further utilize the probabilistic approach. The present study demonstrates how combination of First Order Reliability Method (FORM), Finite Element Method (FEM) and Response Surface Method (RSM) can be useful in the probabilistic assessment of proposed construction of new earth embankment for the doubling of a railway track. It is further highlighted that conventional factor of safety approach when used in conjunction with probabilistic analysis brings rationality in decision making. Also, based on results of slope stability and reliability analysis, it is proposed to incorporate soil nailing to further improve the stability of the earth embankment.

KEYWORDS Earth embankment; Slope stability; Reliability analysis; Finite Element; Numerical analysis; Factor of safety; Railway Track Formation; Soil nailing technique

1 INTRODUCTION

Indian railway is extensively working on "doubling of the railway track" project and while executing the project, it is found that some locations require massive embankment fill for the construction of new track system. Figure 1showsone such case study. Figure 1 shows the elevation of the existing ground and proposed embankment for the new track system. Geotechnical structures, especially embankments or slopes of great heights, constructed using soil as natural material, possess serious stability issues and require detailed investigation for the load carrying capacity, settlement, or deformation pattern as well as stability against failure (Duncan and Wright, 2005). Further challenges are posed due to uncertainties associated with input geotechnical parameters arising due to (i) inherent soil variability, (ii) model transformation uncertainty and (iii) testing errors (Phoon and Kulhawy, 1999a&b; Phoon and Kulhawy, 2005; Uzielli et al. 2007). Conventionally, geotechnical design uses Allowable Stress Design (ASD), in which a reasonable factor of safety based on engineering judgment, experience and confidence level of the designer, is used. Duncan (2000) advocated to use probabilistic approach as a complementary to the deterministic approach for dealing uncertainty and selecting factor of safety based on the extent of variation in the input parameters measured in terms of coefficient of variation (COV%). Several researchers have applied the probabilistic approach in geotechnical applications, such as, Benjamin and Cornell (1970), Ang and Tang (1975, 1984), Harr (1987), Haldar and Mahadevan (2000), Baecher and Christian (2005), Griffiths and Fenton (2007), Phoon and Ching (2018) and highlighted the advantages of assessing the stability or safety as well as performance of geotechnical system using probabilistic approach through case studies.

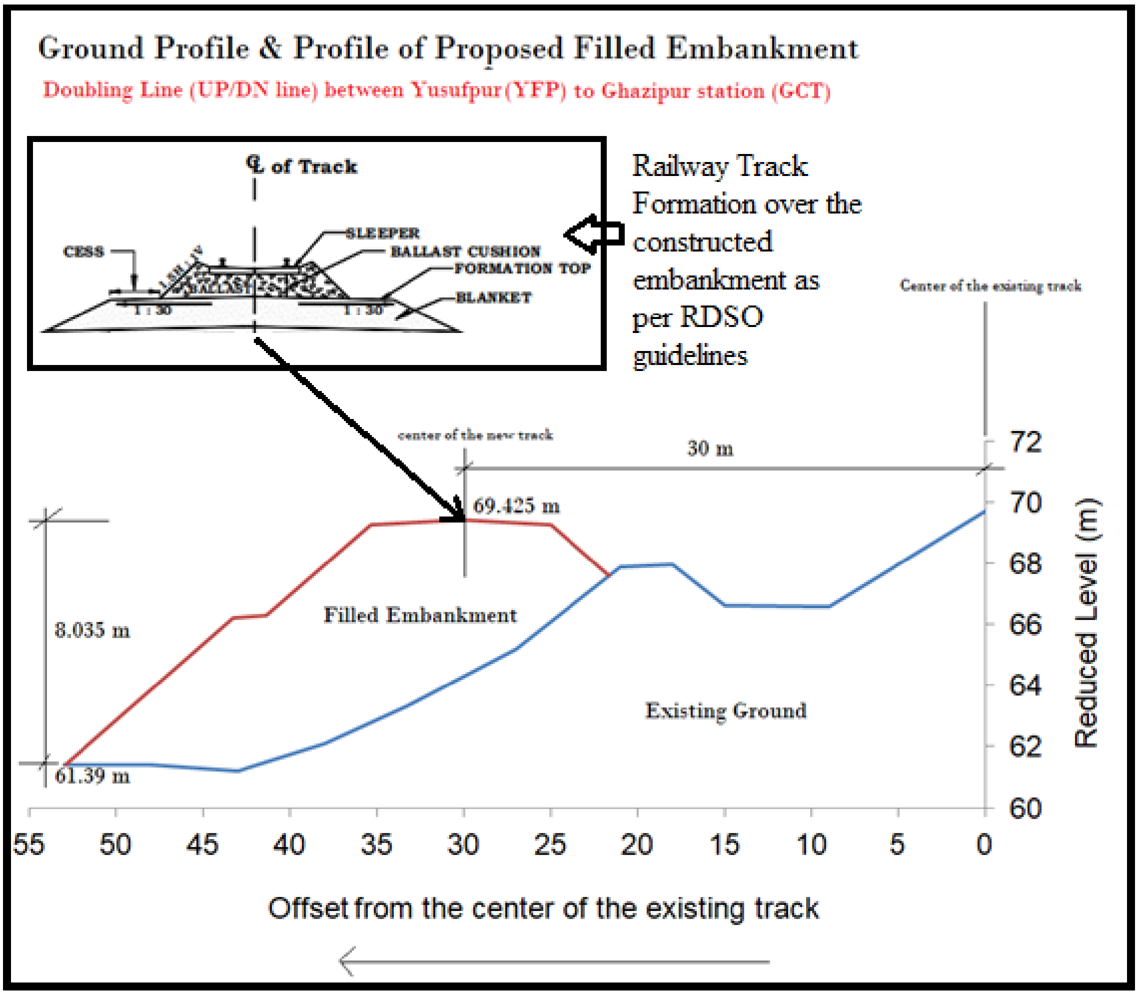

Figure 1. Profile of the existing ground and the proposed embankment for the construction of the new track system

Slope stability of an existing slope or newly constructed embankment slope is one of the major geotechnical challenges and in recent times extensive slope failures are being observed either due to natural triggering factor like rain, earthquake or due to infrastructure development and cutting or filling activities (Shroder et al., 2005; Zhang et al., 2011). Unstable slopes indicated by low factor of safety should be stabilized using suggested ground improvement technique (Holtz et al., 2001). One of the most widely used techniques is soil nailing (Hausmann, 1978; Lazarte et al., 2015). Nailing helps in improving the strength and stiffness of the slope in the same way as reinforcement does in concrete as both materials are considered to be weak in tension. Improvement in strength ensures improved factor of safety while better stiffness means less deformation. Improving factor of safety by all means does not always ensure lower probability of failure. Hence, it is imperative to resolve the issues related to associated uncertainties while estimating geotechnical parameters that are obtained through field or laboratory test results.

A factor of safety indicates qualitative parameter and selecting required factor of safety is based on experience, engineering judgment and confidence level of the designer. It is inherently assumed that the selected factor of safety will take care of all sources of uncertainties in the estimated geotechnical parameters input. On the other hand, in the probabilistic approach, the input parameters are considered as (continuous)random variables and mathematically characterized through parameters of random distribution, such as, mean (μ), variance (σ^2), probability density function (*pdf*) and correlation among input geotechnical parameters through correlation coefficient (ρ) (Baecher and Christian, 2005). In simple terms, random input parameters provide randomness in the output response and the probability of success or failure is measured by fixing the response in the output. The most commonly used method of probabilistic analysis involves estimating of probability of failure (p_f) through techniques like Monte Carlo Simulation (MCS) or performing reliability analysis in terms of an index called "reliability index (β)"by using First Order Reliability Method (FORM) approach as suggested by Hasofer–Lind (1974). The probability of success or failure of a geotechnical structure is defined in terms of an index called as reliability index (β). Reliability is defined as probability of success of a structure or system over a period of time in a given environment of uncertainty. As per USACE (1997) guidelines, reliability index of more than 5 indicates excellent performance, 4-5 very good, 3-4 Average, and less than 3 below average.

The authors advocate the use of probabilistic approach in conjunction with the conventional factor of safety approach to ensure uncertainty is accounted in mathematical framework so that decision making is rational. To justify the authors' point of view, a case of embankment widening for railway track is presented. The case demonstrated how both approaches can be useful in assessing and then improving the performance of the embankment for the railway track to satisfy the RDSO guidelines (RDSO/2020/GE: IRS – 0004). Detailed specifications and thickness of railway track formation layer is provided in the RDSO guidelines for 25T, 30T and 32.5 T axle load, for single-layer (i.e. conventional single blanket layer over embankment fill) and two-layer systems (i.e. comprising blanket and prepared subgrade layer over normal fill). Chapter 5 of the RDSO specification, clause 5.1.1 suggests that railway embankments having a height of more than 6.0 m should be analyzed for its stability. If the factor of safety is less than 1.4, flatter slope or berm/sub-bank can be provided to improve the stability of the slope. Clause 5.4.2 states minimum factor of safety of 1.4 should be adopted against slope failure and to ensure long term stability. Additionally, moving train loads do not need to be considered for embankments higher than 6 m and for low height embankment up to 4.0 m, a minimum factor of safety of 1.6 should be ensured due to overstressing zones and mixed failure mechanism of slope failure and bearing capacity failure of foundation soil. In between 4m to 6m embankment heights, any value in between 1.6 to 1.4 is acceptable.

2 LITERATURE ON SOIL NAILED SLOPE AND ITS NUMERICAL ANALYSIS

Currently, soil nailing is extensively used to stabilize manmade or natural slope, both for filling or excavation work. Early application of soil nails began in 1970s, in France, Germany and USA (Bruce and Jewell 1986). Later, soil nailing spread across the globe and almost all major countries of USA and Europe have adopted it. This is due to soil nailing's versatility, soil nail is cost effective, perform well under earthquake loadings, easy to install, flexible approach and environmentally friendly. However, it should be noted that soil nailing requires skilled manpower, experienced workers, accessible sites as well as suitable and favorable soil and site conditions for the execution of the work. Bruce and Jewell (1986) provided extensive overview of the historical evolution of the soil nailing technique and its popular applications in various successful projects in Europe and USA. Bonita et al. (2006) presented an excellent case of soil nail designed to support29.9m high vertical excavation for the Chinese Embassy in Washington DC, USA. Extensive literature is available on the subject matter (Phear, 2005; Cheung and Ho, 2021). In the year 2015, National Highway Institute (NHI), U.S. Department of Transportation, Federal Highway Administration, Washington, DC, USA provided reference manual on "Soil Nail Walls" (Lazarte et al., 2015). Recently, Ramteke and Sahu (2023) presented extensive review of the work on soil nailing for stabilizing the slopes and retaining walls.

As per FHWA guidelines on nail spacing and its inclination (Figure 2), following guidance are made: Horizontal and vertical spacing = 4ft (1.22 m) to 6ft (1.83 m). Nail inclination should be 10 to 20 degrees from the horizontal, preferably 15°. From Figure 2B, it can be seen that the nailing is expected to be installed (approximately) normal to the slope facing.

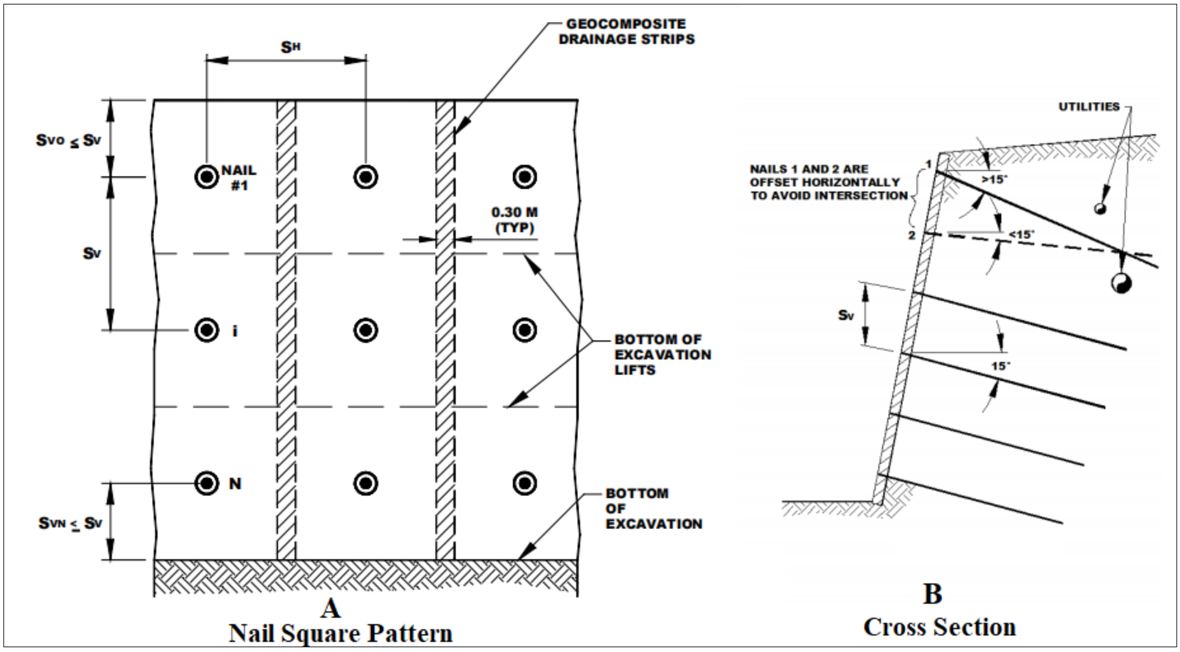

Figure 2 (A) Soil nail (square pattern) indicating horizontal and vertical spacing (B) Soil Nail wall cross-section indicating nail inclination (adapted from Lazarte et al. 2015)

Commercially available finite element tool PLAXIS 2D has been employed extensively for assessing the stability of soil nailed slopes (Babu and Singh, 2009; Moniuddin et al., 2016; Sharma and Ramkrishnan, 2020; Benayoun et al., 2021; Gui and Rajak, 2024). Elahi et al. (2022) employed PLAXIS2D for the parametric study of soil nailed slope through numerical analysis and geometric parameters, such as, slope angle, back-slope angle, soil nail length, spacing and inclination were varied. Results indicated that maximum benefit in terms of enhanced stability is achieved when the nail inclination is in the range of 0-25 degrees from the horizontal, depending on the slope geometry. Similarly, L (length of the nail)/H (height of slope) ratio should be kept 0.9 as there is no further improvement in the stability is recorded beyond that point. Study also suggested that any vertical nail spacing in the range of 1.25 m to 2.0 m is acceptable.

With this brief literature review, the objectives of the present study are defined as:

a) To perform slope stability analysis of the proposed embankment construction with the given geotechnical properties (i) without and (ii) with provision of the 500 mm thick railway blanket layer;
b) To improve the stability of the embankment, if required, using soil nailing technique and providing result analysis of stress-deformation and modified factor of safety through finite element numerical analysis tool, PLAXIS 2D;
c) To perform the reliability analysis of the filled embankment with due consideration of the extent of uncertainty in input parameters after applying combination of Finite Element Method (FEM), Response Surface Methodology (RSM) and First Order Reliability Method (FORM) approach.

3 MATERIAL PROPERTIES AND PARAMETERS

3.1 Soil Properties

Geotechnical properties of the soil material to be used as embankment fill were obtained from the relevant tests performed as per IS code on undisturbed or representative soil samples collected from the field. The same were used for the numerical analysis and stability check of the newly constructed embankment for doubling of railway track. From Table 1, it can be noted that the material soil is classified as SC, which means Clayey sand and it can be compacted toa maximum dry density (MDD) of 18.6 kN/m^3 at Optimum Moisture Content (OMC) of 11.7% under controlled conditions in lab. In the field, it is expected to achieve relative compaction of 98%, which means embankment fill should have a field dry density of18.2 kN/m^3. Other material properties of original ground and embankment fill considered for the numerical analysis are provided in Table 2. Results of geotechnical investigation carried out as per IS 1892: 2021 and geotechnical report prepared through SPT and Bore log data as well as laboratory testing of collected soil samples were used to feed input geotechnical parameters for the numerical analysis. Geotechnical properties of blanket layer used in the numerical analysis are provided in Table 3. Properties are taken from the RDSO guidelines.

Table 1. Geotechnical properties of the soil material for embankment fill (results are obtained from the geotechnical investigation report submitted / taken from the relevant guidelines issued from RDSO)

Sr. No	Name of the test	Result	Relevant IS Code
1	Modified Proctor Test		IS: 2720 – Part VIII
	Maximum Dry Density (kN/m^3), MDD	18.6	
	Optimum Moisture Content (%), OMC	11.7	
2	Atterberg's Limit		IS:2720 – Part V,
	Liquid Limit (%)	30	IS: 2720 – Part VI
	Plastic Limit (%)	21	
	Shrinkage Limit (%)	9	
3	Grain Size Analysis		IS:2720 – Part IV
	% Retained on 4.75 mm sieve	0	
	% retained on 75 μ sieve	57	
	% Passing 75 μ sieve	43	
4	CBR (Soaked condition) %	6.12	IS:2720 – Part XVI
5	Soil Classification as per Indian Standard Code of Practice	SC	IS:1498 (1970)
6	Shear Strength Parameters		IS: 2720 Part XIII
	Cohesion (c), kPa	50	
	Angle of internal friction (ϕ°)	24	

Table 2. Geotechnical properties of soil used for the numerical analysis (results are obtained from the geotechnical investigation report submitted / taken from the relevant guidelines issued from RDSO)

Sr. No	Geotechnical Properties	Unit	Numerical values (Foundation soil)	Numerical values (Filled Embankment)
1	Material Model	-	Mohr Coulomb	Mohr Coulomb
2	Material Type	-	Drained	Drained
3	Unit Weight (g) (Both saturated and unsaturated)	kN/m^3	18.60	18.22 (*Assuming RC 98% achieved in the field*)
4	Elastic Modulus (E)	MPa	80	100
5	Poisson's Ratio	-	0.35	0.40
6	Cohesion – shear strength Parameter	kPa	1.0	50
7	Angle of internal friction (ϕ)	°	28	24

Table 3. Geotechnical properties of the blanket layer used in the numerical analysis (results are obtained from the geotechnical investigation report submitted / taken from the relevant guidelines issued from RDSO)

Sr. No	Geotechnical Properties	Unit	Numerical values (Blanket layer of thickness 500 mm)
1	Material Model	-	Mohr Coulomb
2	Material Type	-	Drained
3	Unit Weight (γ) (Both saturated and unsaturated)	kN/m^3	20.0
4	Elastic Modulus (E) as per RDSO 2020 guidelines	MPa	120
5	Poisson's Ratio	-	0.3
6	Cohesion – shear strength Parameter	kPa	0.1 (to avoid numerical instability)
7	Angle of internal friction (ϕ)	°	34

3.2 Plate Elements Modeled as Concrete Sleeper

Table 4 provides details of the precast concrete sleeper used in the railway track system. Based on the grade of the concrete, the elastic modulus (E_c) is taken as 30 GPa and cross-sectional area (A) as well as moment of inertia (I) values are evaluated based on the geometry of the concrete sleeper. For modeling the concrete sleepers as plate element in 2D analysis, the equivalent EI and EA values are calculated and given as input for assigning the material properties of the plate element and same is provided in Table 5.

Table 4. Parameters of concrete sleeper

Sr. No.	Grade of concrete sleeper	M60
1	Elastic Modulus of concrete sleeper (E)	30 GPa
2	Size of sleeper L × B × D	Overall length 2478 mm joined by two RCC blocks of dimensions 722 mm × 295 mm × 251 mm
3	Moment of Inertia (I) about the cross section ($I = BD^3/12$)	388742420.4 mm^4
4	Area of cross section of concrete sleeper (A)	74045 mm^2

Table 5. Properties of plate element for numerical modeling and analysis

Sr. No	Property	Unit	Numerical Value
1	Material Type	-	Elastic
2	Axial Stiffness (EA)	kN/m	2221350
3	Flexure stiffness (EI)	$kN/m^2/m$	11662
4	d (equivalent thickness)	m	0.251
5	w (specific weight)	kN/m/m	1.34
6	Poisson's ratio	-	0.15

4 RESULTS OF ANALYSIS AND DISCUSSION

4.1 Without Soil Nailing Application

As per RDSO guidelines (Specification No RDSO/2020/GE: IRS-0004), to simulate axle wheel load on the track, 50 kPa of UDL is applied over a length of 3.0 m and the numerical analysis is performed considering the following two cases

Case A: without any provision of blanket layer

Case B: with provision of 500 mm blanket layer

For the **Case A** analysis, Figure3 shows the numerical model developed for the static analysis of embankment. The problem is to be analyzed assuming plane strain conditions, and considering 15 node triangular elements, as well as adequately setting the geometry dimensions (Left = -100m, Right = 10 m, Bottom = -20 m and Top = 20 m) and fixing the measurement units as L = meter, Force = kN and Time = second. It is proposed that the new track system will be approximately 30.0 meters away from the C/C distance from the existing track and the filled embankment of height 8.035 m will be placed over the existing ground as shown in Figure 1**,** which was used to create the geometry of the numerical model.

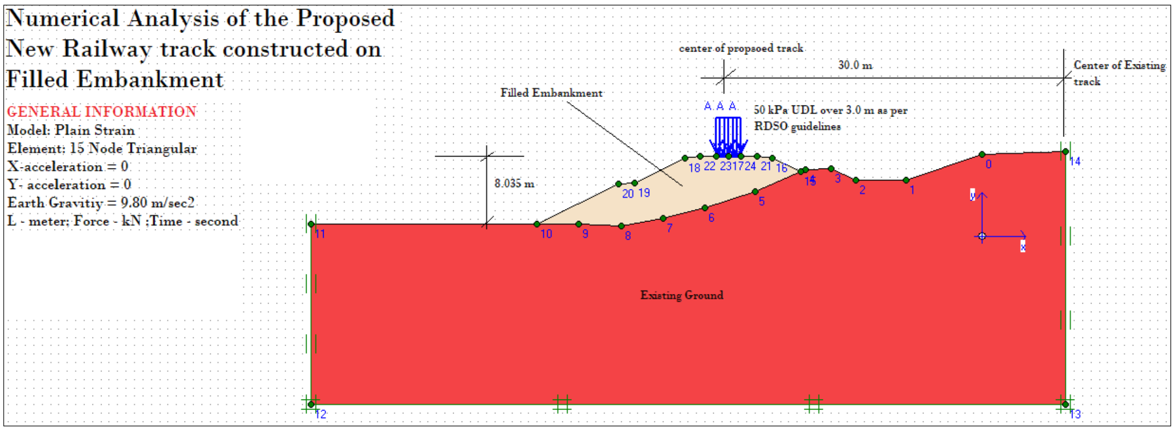

Figure 3. Numerical model of the proposed filled embankment with loading and applied boundary conditions

Figure4 provides results of the numerical analysis after application of track load and development of deformation pattern for case A analysis. Similar analysis was performed for Case B analysis with the provision of blanket layer (500 mm). The results of the numerical analysis are presented in Table 6.

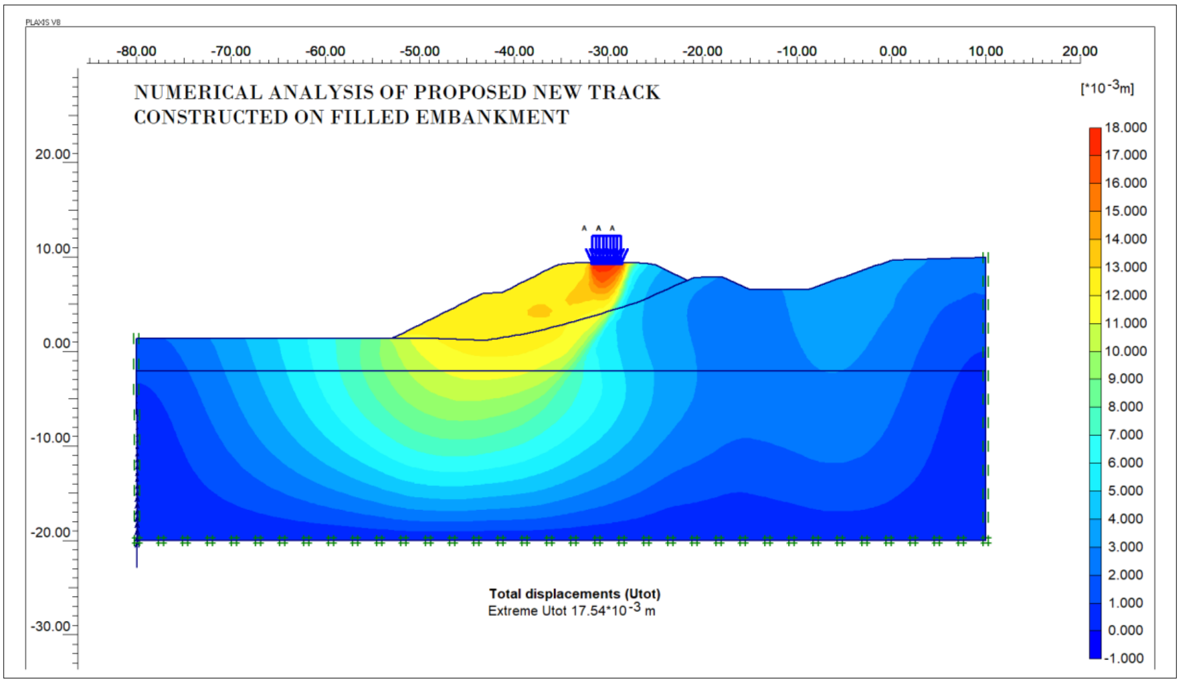

Figure 4. Total deformation developed in the numerical model (without soil nailing)

Table 6. Results of the numerical analysis without and with the provision of blanket layer

Filled Embankment	Without blanket layer	With blanket layer
Factor of Safety	1.06	1.05
Deformation	17.54 mm	18.03 mm

It can be noted that as per guidelines laid down in RDSO manual, a factor of safety less than 1.40 is not acceptable and hence there is a need to improve the stability of the filled embankment.

4.2 With Soil Nailing Application

Plate elements are used to model the soil nails. Soil nails are basically HYSD (high yield strength deformed) bars of diameter 25mm, 32 mm or 40 mm depending on the requirements of design. In the present case, 32 mm diameter bar is proposed and accordingly the equivalent value of EI and EA are evaluated. The properties taken for the analysis is provided in Table 7.

Table 7. Properties of plate element for numerical modeling and analysis using soil nail

Sr. No	Property	Unit	Numerical Value
1	Material Type	-	Elastic
2	Axial Stiffness (EA)	kN/m	160850
3	Flexure stiffness (EI)	$kN/m^2/m$	10.30
4	d	m	0.028
5	w	kN/m/m	0.063
6	Poisson's ratio	-	0.15

Spacing of nails were randomly varied in the c/c range of 1.5to 2.5 m spacing to simulate the field condition. Inclination of the soil nails were such that they are approximately at 90° angle or normal to the slope facing. Nailing on the horizontal face was inclined in such a way that they are parallel to the nails provided on the slope face as shown in the Figure 5. The numerical analysis procedure remains the same as section 4.1, with the exception of activating the soil nails prior to factor of safety calculation. Deformation pattern is shown in Figure 6.

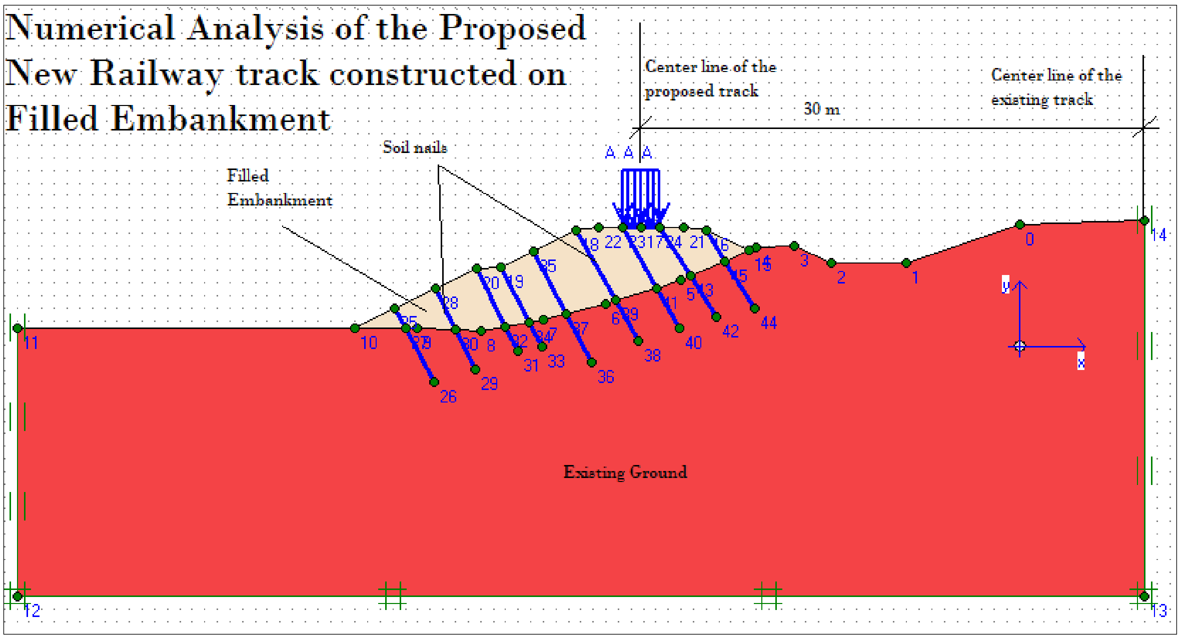

Figure 5. Numerical model for the filled embankment with provision of soil nails

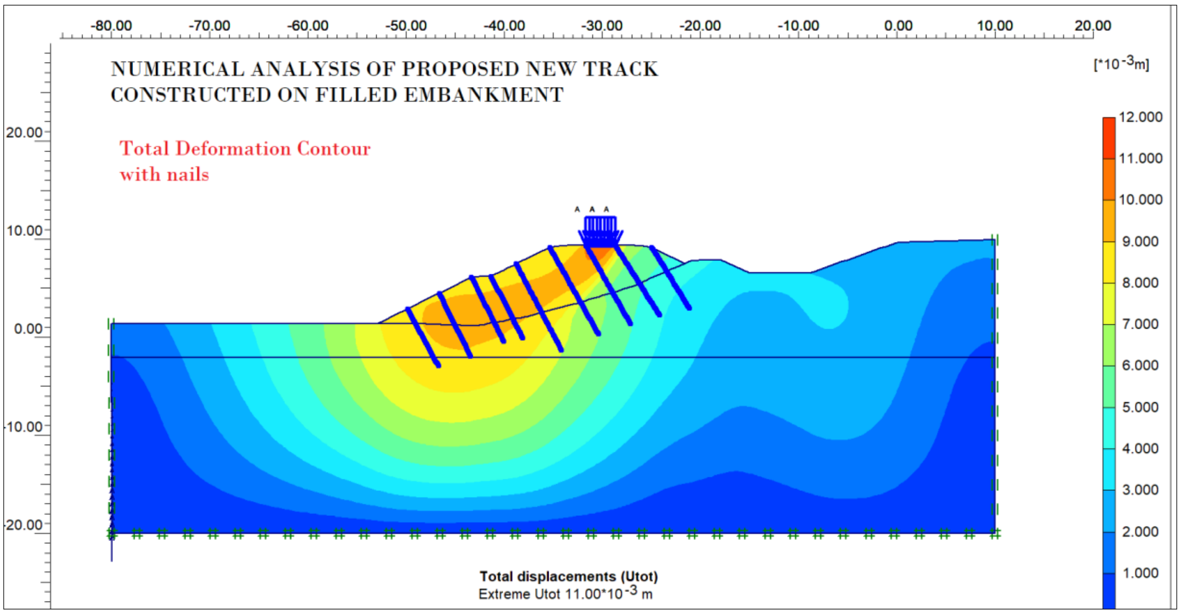

Figure 6. Total deformation pattern and contour of filled embankment with soil nails

Table 8 provides the results of the numerical analysis with provision of soil nails, performed for both the cases, i.e., without and with blanket layer. Soil nailing also improves the geotechnical properties and strength of the material thereby improving upon the safety of the structure. The same is depicted in the results that show improvement in the factor of safety and reduction in the total deformation when compared to the corresponding value reported in Table 6.

Table 8. Results of the numerical analysis using soil nails without and with the provision of blanket layer

Filled Embankment	Without blanket layer	With blanket layer
Factor of Safety	1.59	1.51
Deformation	11.00 mm	12.89 mm

4.3 Consideration of Uncertainty and Probabilistic Approach

To consider the uncertainty in the input geotechnical parameters, published literature by Duncan (2000) is referred and coefficient of variation in the estimated mean values are taken into account as per Table 9.For the probabilistic analysis, an explicit functional relationship between input geotechnical parameters and output response, i.e., factor of safety (FOS) is established using 2^n full factorial design explained in Response Surface Method (RSM) approach (Myers et al., 2016). To elaborate, for 3 input geotechnical parameters, there will be 8 combinations representing the 8 corners of the cube. The center of the cube represents the mean value (μ) of the input parameters and coordinate of each corner is taken as $\mu \pm m\sigma$, where mis taken from 1 to 3.

Table 9. Coefficient of variation (CoV%) considered in the geotechnical input parameters

Sr. No	Geotechnical Properties	CoV%
1	Unit Weight (γ)	18
2	Elastic Modulus I	12
3	Poisson's Ratio	-
4	Cohesion – shear strength Parameter	30
5	Angle of internal friction – shear strength parameter	20

In the present study, the value of mis taken as 1.65 and standard deviation (σ) is calculated from the assumed value of coefficient of variation (CoV%) in the input parameters. For Such 8 combinations of 3 input geotechnical parameters, i.e.γ, c and ϕ, the factor of safeties evaluated are provided in Table 10.

Table 10. Combination of input geotechnical parameters (after improvement due to nailing) and corresponding output from numerical analysis

Sr. No.	γ	c	ϕ	γ	c	ϕ	FOS
1	+	+	+	24	7	40	1.86
2	+	+	-	24	7	20	1.32
3	+	-	+	24	3	40	1.78
4	+	-	-	24	3	20	1.13
5	-	+	+	13	7	40	1.99
6	-	+	-	13	7	20	1.45
7	-	-	+	13	3	40	1.93
8	-	-	-	13	3	20	1.20

From data analysis tool pack available as inbuilt option in the Microsoft excel; linear regression, based on least square error approach is performed using input and output data of Table 10. The following regression equation is obtained to depict an explicit functional relationship between input geotechnical parameters and output response,

$$FS = 0.668 - 0.0106(\gamma) + 0.0363(c) + 0.0308(\varphi) \quad (1)$$

While producing above equation, it is assumed that input geotechnical parameters are uncorrelated normally distributed and based on the mean and variance in the input geotechnical parameters, the mean and variance of output response, i.e., FS is obtained as indicated in Table 11.

Table 11: Mean and standard deviation in the FOS, i.e. output random response from numerical analysis

Mean FS	1.579
Variance FS	0.0385
Standard Deviation FS (σ_{FS})	0.196

Using the mean and variance in the FS value, the reliability index (β) is calculated using the following equation:

$$\beta = (FS - 1)/\sigma_{FS} \quad (2)$$

Using the data in Table 11, The reliability index value is obtained as 2.95, [i.e. (1.579-1)/0.196 = 2.95] indicating below average performance of the filled embankment based on the extent of uncertainty involved in the input geotechnical parameters. Hence, it can be stated that although achieving high and acceptable value of factor of safety in the deterministic terms does not ensure the good performance in the given environment of uncertainty in the geotechnical parameters. However, it should be noted that these observations are based on the assumed value of CoV% obtained from the literature. Real estimation is possible when site specific test data are available. The approach gives an insight of the importance of probabilistic analysis when used in conjunction with the deterministic approach. Both are complementary to each other and should be utilized for better decision making.

5 CONCLUSIONS

a) Results of the numerical analysis indicate that inclusion of blanket slightly reduces the FOS and increases the settlement. This is due to the fact that an addition layer of blanket, additional load is introduced at the top of the embankment and this cause additional stress on the filled embankment thereby reducing the factor of safety and increasing settlement.
b) The initial slope stability analysis of the new embankment fills for expansion of rail track yield a factor of safety below 1.40, and thus not acceptable as per RDSO standard guidelines. Therefore, ground improvement technique like soil nailing is requires. After soil nailing, the factor of safety obtained increases and is much higher than the minimum expected value of 1.40 as per RDSO guidelines.
c) Although, factor of safety value is acceptable as per the RDSO guidelines, reliability analysis based on the assumed value of coefficient of variation in the input geotechnical parameters, using combination of FEM, RSM and FORM demonstrated that the new embankment fill has reliability index of less than 3, indicating below average performance.

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