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A new approach to estimate the factor of safety for rooted slopes with an emphasis on the soil property, geometry and vegetated coverage

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Abstract. 180 different 2D numerical analyses have been carried out to estimate the factor of safety (FOS) for rooted slopes. Four different types of vegetated coverage and a variety of slope geometry considering three types of soil have been evaluated in this study. The highly influenced parameters on the slope's FOS are determined. They have been chosen as the input parameters for developing a new practical relationship to estimate the FOS with an emphasis on the roots effects. The dependency of sliding mode and shape considering the soil and roots-type has been evaluated by using the numerical finite element model. It is observed that the inclination and height of the slope and the coverage type are the most important effective factors in FOS. While the soil strength parameters and its physical properties would be considered as the second major group that affects the FOS. Achieved results from the developed relationship have shown the acceptable estimation for the roots slope. The extracted R square from the proposed relationship considering nonlinear estimation has been achieved up to 0.85. As a further cross check, the achieved R square from a multi-layer neural network has also been observed to be around 0.92. The numerical verification considering different scenarios has been done in the current evaluation.

Keywords: rooted slope; numerical; relationship; factor of safety

1. Introduction

Research on the effects of plants' roots on slope stability has widely been studied in the last 40 years. The impact that grass, shrubs and trees may have on slope stability has been proved by several researchers. Rooted slope interactions are highly complex and this has hampered the efforts to estimate the instability analysis (Rienstenberg 1987, Zhou *et al*. 2015). Although the positive effect of vegetation growing on the slope stabilization has been proved in some cases, this general assumption is not a suitable response (Sommers *et al*. 2000, Kokutse *et al*. 2016). A large number of scientific studies on the influence of precipitation events and deforestation on the slope stability in highland areas reported the troubles in numerous parts of the world (DeGraff 1989).

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Moreover, results of the previous research show that the risk of landslide and slope instability in mountain areas will be increased during the first year after wood harvesting physical activities (Swanston 1974). A majority of studies have proved that the soil cohesion value depends closely on the values of roots type and volume. Hence, meaningful correlations relating to cohesion increase because of roots effects have achieved in previous research (Rienstenberg 1987, Van Beek *et al*. 2005).

It is reported that slope stability highly depends on the values of soil strength parameters and roots type mechanical behavior which are related to local climate and nature (Charlafti 2014, Stokes *et al*. 2009). Several studies have been carried out in order to understand how plants can improve slope stability. The correlation of root's tensile resistance of different species growing on slopes with roots cellulose content evaluated by Genet *et al*. (2007). Also, a study about the effects of local top climate on cut slope restoration success by herbaceous plants has been done by Cano *et al*. (2002). The additional strength in chalky and clayey soils due to the presence of roots of some plant species by the laboratory shear tests have quantified by Operstein and Frydman (2000). Moreover, the laboratory and field work of Wu (1995, 1988) showed that the plant's root is capable to increase soil shear strength. The mechanism of reinforcement and cohesion increase have been investigated by other previous researchers (Terzaghi 1950, Gray and Ohashi 1983, Wu *et al*. 1988).

Most of studies have had an aim to slope stability evaluation and focused on different ways to assess slope stability (Griffith and Lane 1999, Baudin *et al*. 2000, Xie *et al*. 2004, Kokutse 2008), such as nailing, anchorage, piling and so on (Sommers *et al*. 2000, Kokutse *et al*. 2016). Also, the stability of different structure considering the effects of soil, fluid and dynamic forces have been evaluated by using different analytical and numerical method with an emphasis on soil structure interaction and fluid-structure soil interaction effects (Maedeh *et al*. 2016, 2017a, 2017b).It is proved that the roots reinforcement has the positive influence on the soil due to their tensile resistance and frictional properties most of the time (Wu *et al*. 1979, Waldron 1977). The variety types of root reinforcement models have been evaluated to better understand rooted slope reinforcement mechanism (Wu *et al*. 1979, Waldron and Dakessian 1981, Genet *et al*. 2007,

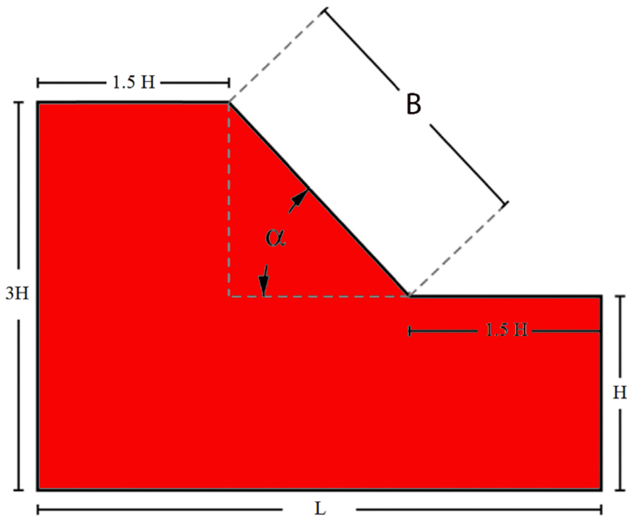

Fig. 1 The schematic view of evaluated slope and its geometry

Kokutse 2008). Grass, shrubs, trees or a combination of any two or all three types of vegetation are capable to grow on the slope generally. Moreover, apart from the mechanical effects of vegetation, the mechanism of roots growing and its weight as a surcharge are the ones that are considered most of the time (Nilaweera and Nutalaya 1999, Kokutse *et al*. 2016).

The first aim of the present study is to develop a new practical relationship to estimate the FOS for the rooted slope considering roots type, slope geometry and soil properties. This type of practical relationship would useful for primary estimation of FOS for natural slopes, side walls of main roads, highways and dams or so on. Another aim of the current work is to evaluate the effect of slope geometry, local soil strength properties and local vegetation type on the factor of safety (FOS) of the rooted slopes. Four different types of widespread roots (grass, shrubs, young forest and mature forest) are considered for slope coverage. Their growing condition in different cases of normal weather (15-40ºC) would be considered. Different types of slope geometry with three types of local soil (clay, sand and silty-sand) have been investigated in this study. The strength factors reduction by using 2D numerical analysis for each condition have been carried out to estimate each case's FOS. Moreover, the statistical-analytical analysis is the base of developing the proposed relationship. The results obtained from the practical relationship would be compared with those of a multi-layer neural network and they will be explained.

2. Material and methods

The finite element method has been used to estimate the slope stability according to the effect of roots coverage, slope geometry (height and inclination) and soil strength mechanical properties. The additional cohesion technic in Mohr-Coulomb's low has been considered for modelling the roots and vegetation cover effects. Furthermore, the uniform load is assumed as the surcharge of the vegetation cover's weight. The height and angle of slopes are regarded as the geometrical parameters while soil mechanical properties are attributed to the effects of roots and additional cohesions.

A schematic figure of the evaluated slope geometry is illustrated in Figure 1. Two significant parameters H (the height of base of slope) and Alpha (the horizontal angle of slope) are showed in the figure. In this study, the range of H has considered from 5 to 20 m (5, 10, 20) and the range of inclination evaluated from 15 to 55 (15, 30, 45, 55) degrees. The 2D area of generated slope geometry has been meshed by using the adaptive triangular elements. The fine and the very fine mesh size by using the 15-point element have been generated in the body of slope and roots part, respectively.

The influence of roots on the shear resistance for a soil layer as the additional cohesion of the soil has been performed by Wu *et al*. (1979). The following relationship has been developed to estimate the increase of soils shear strength with an emphasis on the roots type (Eq.1).

$$C_{R=t_R}(\cos\emptyset\tan\emptyset'+\sin\emptyset) \quad (1)$$

Where t_R is the tensile strength of roots per unit area of soil and Θ is the angle of shear rotation. Five different analysis cases considering four types of roots coverage have been evaluated in the current work. Due to Eq.1 the additional cohesion (kPa) with an emphasis on soil depth has been shown in Table 1.

The strength parameters for the evaluated soil have been shown in Table 2. Three different types of soils (clay, sand and silty sand) are considered for the roots effect. Also, the mechanical

Table 1 Additional cohesion of soil according to type of vegetated coverage and depth of surface layer (Kokutse *et al*. 2016)

Roots type	Depth on the slope surface			
	0-0.5 m	0.5-1 m	1-1.5 m	1.5-2 m
None	0	0	0	0
Grass	0.5	0	0	0
Shrubs	1.5	0.75	0	0
Young forest	2.8	1.5	0.5	0.3
Mature forest	5	1.5	0.5	0.3

Table 2 The properties of investigated soil type in the current study and their strength parameters

Mechanical properties	Clay	Sand	Silty-sand
Dry density [$kN.m^{-3}$]	16	17	17.5
Young modulus [kPa]	10000	13000	11500
Poission ratio	0.35	0.3	0.32
Shear modulus [kPa]	3704	5000	4600
Internal angle of friction	20	30	25
Cohesion [kPa]	15	1	5

behavior of soil has been assumed to have an elastoplastic nature by using the Mohr-Coulomb failure criterion.

The 2D model of slope geometry is shown in Fig. 2. Its mesh is consisted of triangular 15 points elements in FEM model. The input data of the numerical model is considered from Kokutse (2003), Pretzsch *et al*. (2014), Pretzsch (2010) and Kokutse *et al*. (2016). Moreover, a basic statistical analysis for collecting the data related to roots' distribution has been performed. The stability analysis method consisted of successively reducing soil strength parameters (cohesion, the internal angle of friction) while keeping the gravity constant. In this study, the value of FOS was the parameter that corresponds exactly to a large jump in a nodal displacement computed at a given node close to the soil surface indicating failure (soil slide) (Griffith and Lane 1999, Dawson *et al*. 2000).

To define incorporation for the root's additional cohesion and its variation considering the depth in the numerical model, a 2-meter depth layer from the surface of the slope has been generated and is divided into four sublayers (0-0.5 m, 0.5-1 m, 1-1.5 m, 1.5-2 m). The additional soil cohesion in each layer has been defined separately and is added to the natural cohesion of the base soil. This procedure has applied for each of the four different roots types. To complete the FEM modelling, the static boundary condition has been defined for all sides, edges and base of the modelling area. The fixed base condition has been assumed for the base of FEM model. While the sides of the FEM model have been fixed in the horizontal direction (Ji *et al*. 2012). Furthermore, the constant gravity is applied in order to consider the geostatic stress.

The surcharge of W due to the presence of trees has been defined by using uniformly distributed load and applied on the slope surface. Its value has been considered 0 for cases of none vegetated coverage, grass and shrubs. While in cases of mature and young forest, its value has been considered 0.6 kPa. The mentioned value is extracted from the soil by a plantation of 350 trees/ha of maritime pine (Matsui and San 1992, Dawson *et al*. 2000, Rocscience Inc. 2001).

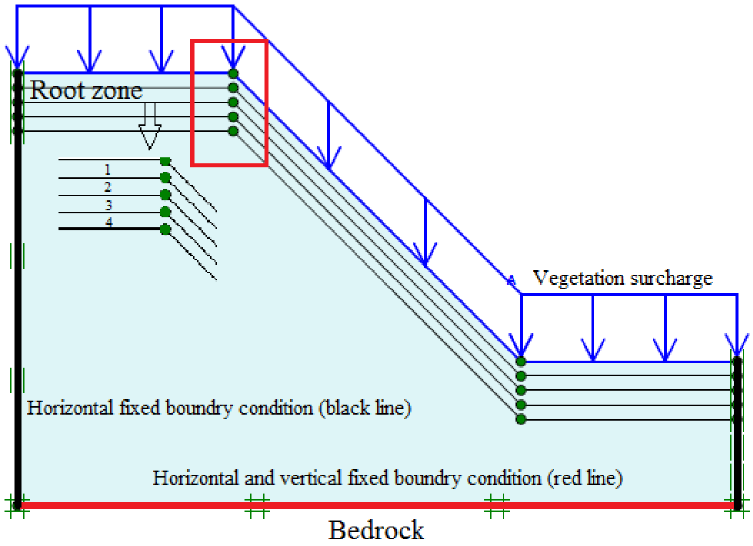

Fig. 2 Schematically view of numerical modelling considering boundary condition, surface layers and slope surcharge

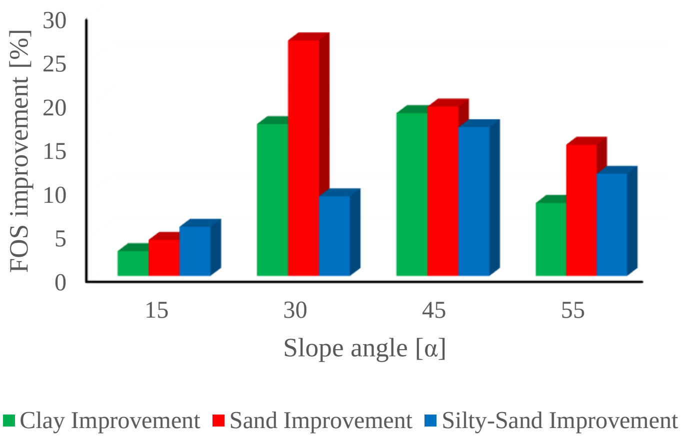

Fig. 3 Rising trend percent for the factor of safety considering roots additional cohesion

3. Results and discussion

3.1 Results of numerical analysis

The influence of root's additional cohesion considering the constant condition of slope height has been evaluated by performing 180 different numerical tests. Achieved result of FOS analysis shows that in case of sandy soil considering mean of height, roots effect and slope inclination the highest improvement of FOS would be occurred. The result showed that slopes with 30 degrees inclination have the highest sensitivity for FOS change.

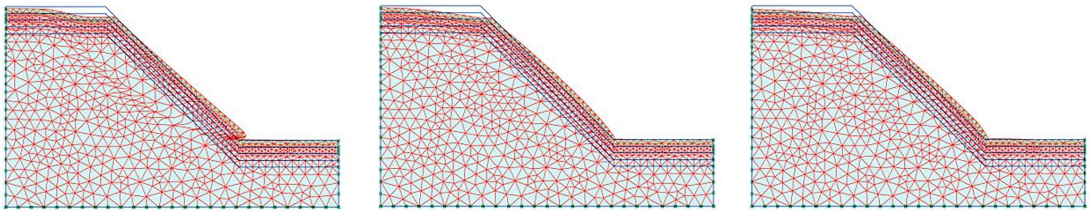

Fig. 4 Type of the slope sliding due to different soil types (left to right: clay, sand, silt-sand) obtained by finite element analysis

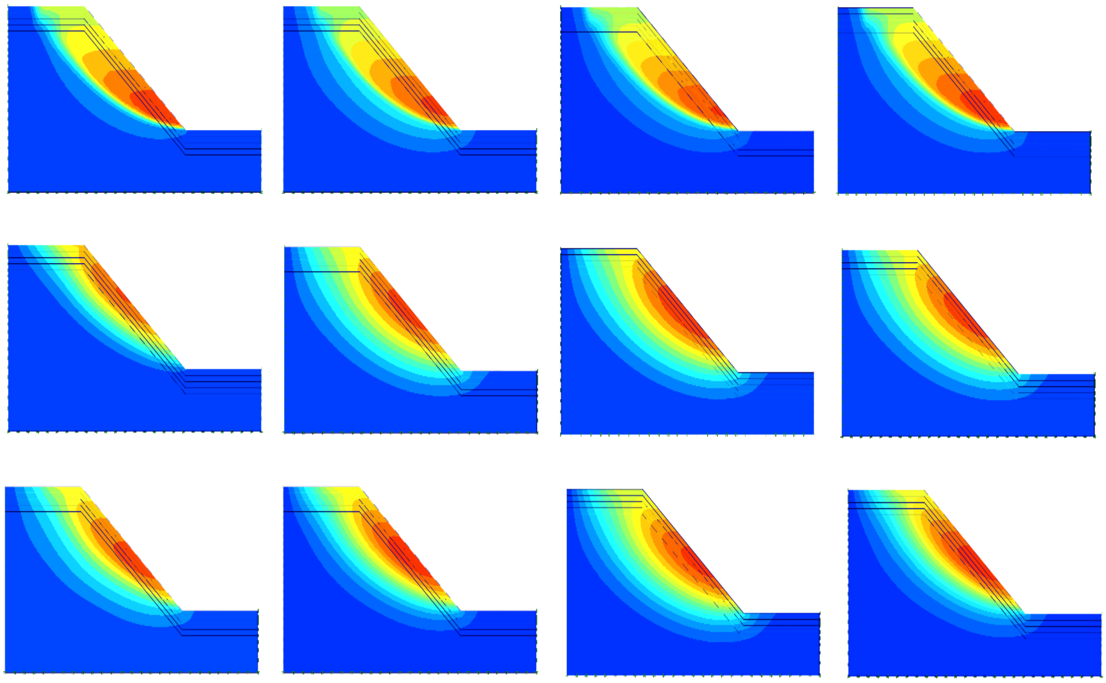

Fig. 5 The sliding shape obtained from numerical analysis. From right to left (Grass, shrubs, young forest and mature forest), From top to down (clay, sand and silty sand) Soil 1 to 3 grass to forest

While considering the different types of roots reinforcement, the same effects of improvement have been observed in case of 45-degree slope's inclination. Considering achieved results from FEM analysis maximum impact of the combination in roots and clay to increase the FOS in case of 15-degree inclination is reported to be 3 percent. While considering the same geometry condition, it is observed that the FOS improvement has been recorded about 5 percent in case of sandy soil. In case of slope inclination of 45 degrees, the FOS improvement has been detected approximately 19 percent. The maximum improvement effect of FOS has been illustrated in case of sand. Other values of mean FOS improvement considering the roots effect are presented in Fig. 3.

Due to the numerical modelling's results, the different types of probable sliding have been illustrated in Figure 4. It is observed that in case of the constant condition in slope geometry and

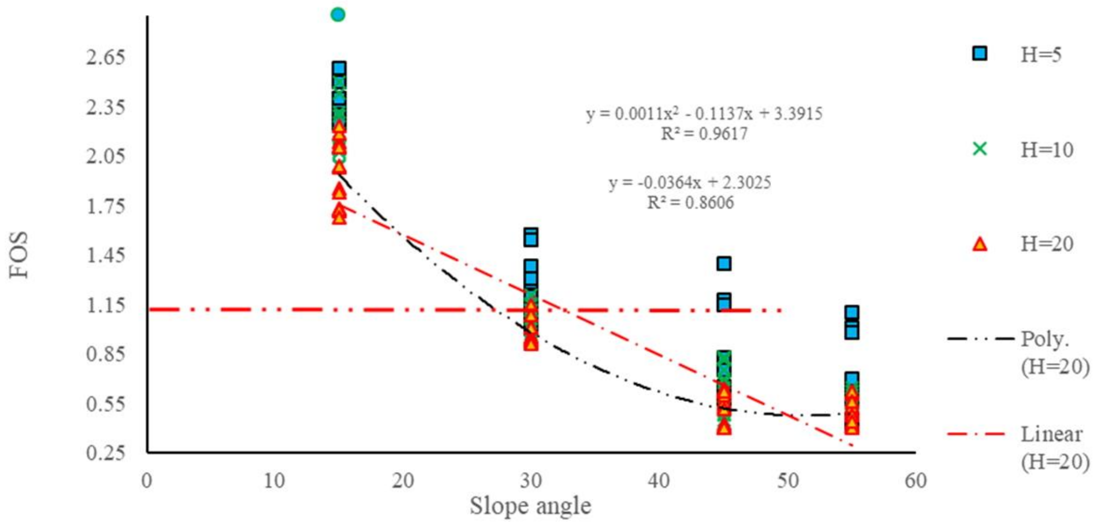

Fig. 6 Mean of FOS as a function of slope angle for various slope heights

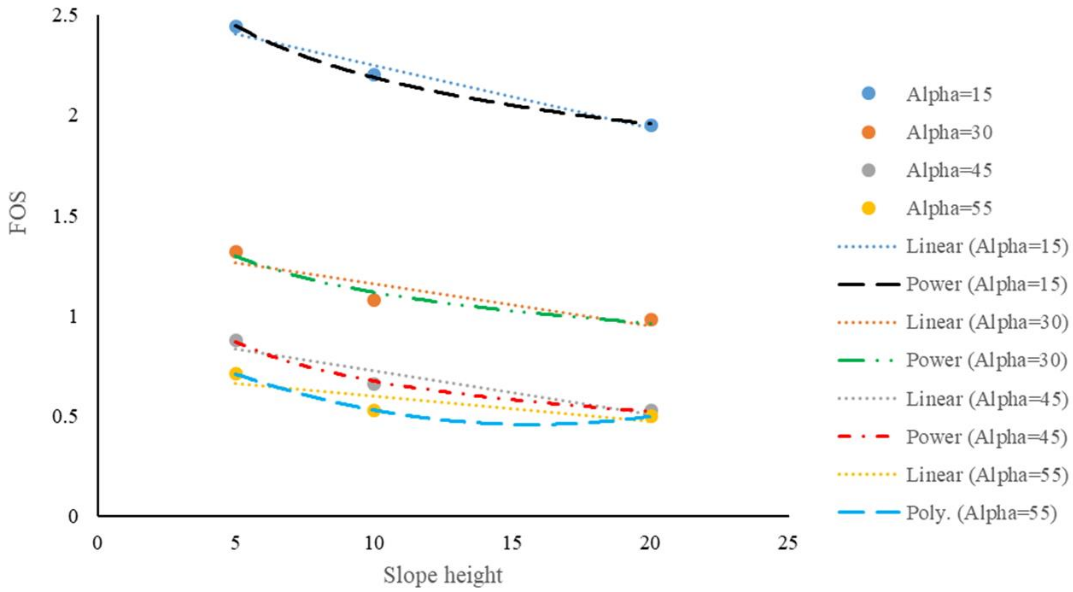

Fig. 7 Mean FOS as a function of slope heights for different slope angles

vegetation type coverage, the different types of sliding may be occurred. Maximum displacement has been occurred clearly in case of clayey soil, at the base of the slope. While the higher value of displacement has observed in the middle of slope surface in case of silty-sand and sandy soil.

The probable failure wedges for the constant height and slope inclination are illustrated in Figure 5. It is observed that the type of failure wedges depends clearly on the type of root coverage and soil properties. It has resulted that by changing the type of roots coverage from grass to mature forest the depth of sliding will be increased. Furthermore, the depth of sliding wedge for clay and silty-sand have been estimated considerably less than the sand condition. It means that, by

Table 3 Linear and nonlinear equation to estimate the FOS considering slope height

	Slope angle [α]			
	15	30	45	55
Linear	y = -0.0316x + 2.565	y = -0.0209x + 1.37	y = -0.0219x + 0.945	y = -0.0125x + 0.7255
R square	0.9685	0.8311	0.8003	0.7022
Nonlinear	$y = 3.1743x^{-0.162}$	$y = 1.5674x^{-0.366}$	$y = 1.5674x^{-0.366}$	$y = 0.0022x^2 - 0.0689x + 0.9997$
R square	0.9981	0.994	0.994	1
R square difference [%]	3	16.3	20	30

Table 4 The statistical results of soil strength parameters based on results of the numerical analysis

Statistical result	Alpha [Degree]	Height [m]	Ø [Degree]	C [kPa]	L1 [kPa]	L2 [kPa]	L3 [kPa]	L4 [kPa]	ɣ [kPa]	Elastic Modulus [kPa]	Ʊ
Mean	36.25	11.67	25.00	7.00	9.06	7.69	7.16	7.06	16.83	11500.00	0.32
N	180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00
Std. Deviation	15.20	6.25	4.09	5.90	6.15	5.94	5.91	5.91	0.63	1228.16	0.02
Std. Error of Mean	1.13	0.47	0.31	0.44	0.46	0.44	0.44	0.44	0.05	91.54	0.00
Minimum	15.00	5.00	20.00	1.00	1.00	1.00	1.00	1.00	16.00	10000	0.30
Maximum	55.00	20.00	30.00	15.00	20.00	16.50	15.50	15.30	17.50	13000	0.35
Range	40.00	15.00	10.00	14.00	19.00	15.50	14.50	14.30	1.50	3000	0.05
Variance	230.97	39.11	16.76	34.86	37.85	35.24	34.90	34.87	0.39	1508379.89	0.00

increasing the strength parameters of the soil the depth of failure wedge would be increased.

The effect of different types of roots on slope sliding with an emphasis on the slope's height and inclination has been shown in Figure 6. Regardless of the soil type, it is observed that a meaningful nonlinear relationship has presented between the slope's inclination and FOS. A nonlinear equation by R square 0.96 for correlation between the inclination and FOS has been generated. While considering the linear regression, the R square is decreased to 0.86. The achieved result shows that the slope angle has the highest influence on the FOS. In case of higher slopes and constant inclination, neglecting the root and soil's effect, it is observed that the maximum changing for FOS would be 85 percent. While in case of the short slope, mentioned changes has been estimated up to 37 percent. The achieved result showed that the slopes with the inclination of fewer than 30 degrees and less than 15 meters height can be categorized as the safe slopes.

The result of FOS evaluation considering the roots effect and the slopes geometry has been shown in Fig 7. It is observed that contrary to the inclination dependency, the achieved relationship between FOS and slope height is linear with the acceptable values of R square. In case of linear regression, the result shows that increasing the inclination can decrease the value of R square. Moreover, the extracted R square shows that in case of higher value of inclination the nonlinear regression has a good estimation for the FOS. Four different nonlinear relationships with an

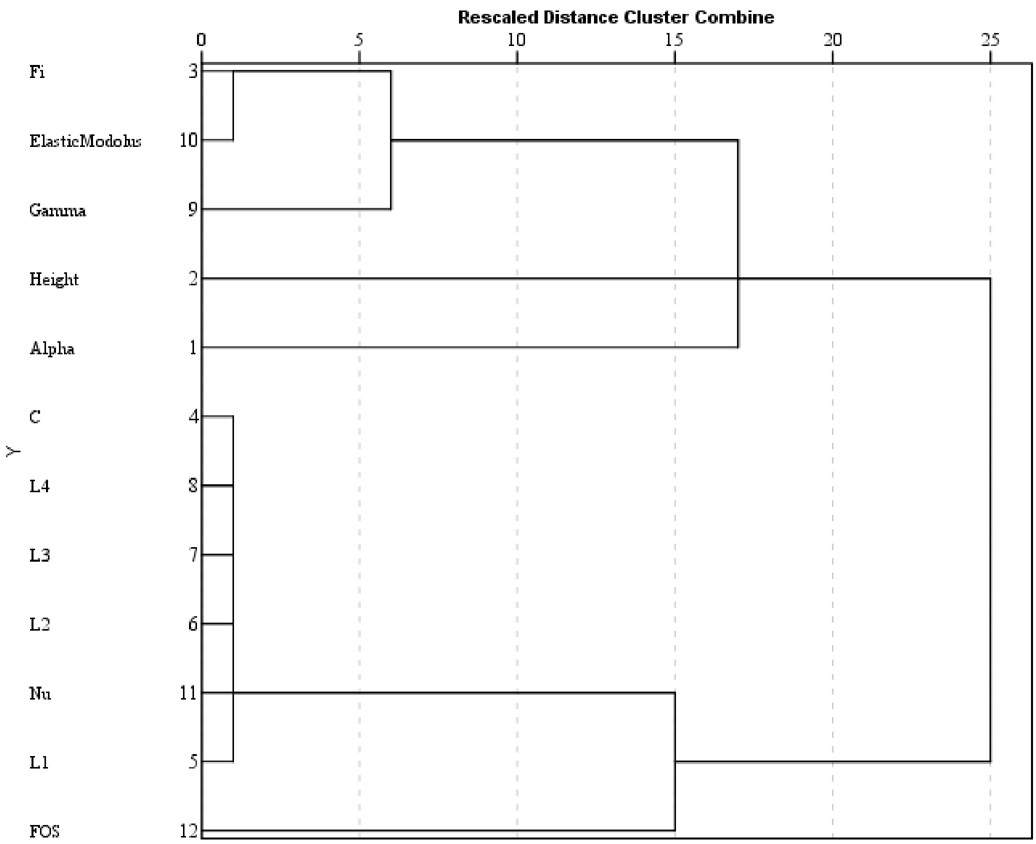

Fig. 8 Correlation dendrogram for sets of soil strength parameters and slope geometry in influencing the slope's FOS

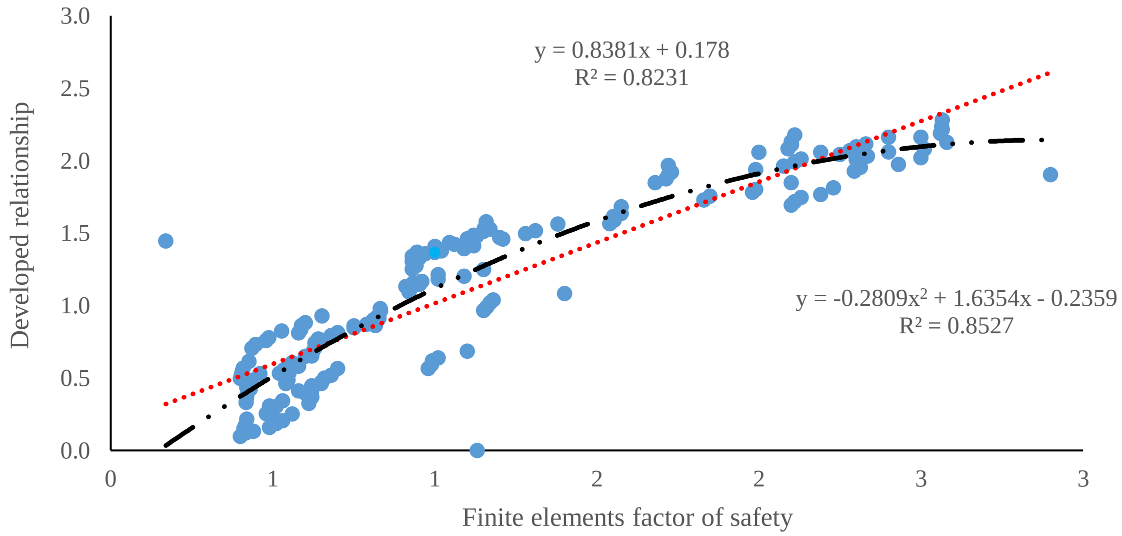

Fig. 9 Comparative results of developing relation FOS estimation and achieved results of numerical analysis

emphasis on slope angle and height to estimate the FOS are presented in Table 3.

3.2 Results of statistical analysis

Regarding the result obtained from the numerical models, the following statistical assessment has been carried out to find the mean, standard error, minimum, maximum, range and the variance of each considered parameter. Where new parameters L1 to L4 have been generated as the representative of the additional cohesion factor for slope's surface layers in the numerical modelling. Preliminary evaluation from the results of 180 different numerical analyses are reported in Table 4.

Results show that the highest mean value for the additional cohesion has occurred in the first divided layer (L1). Also, the mean of height has been calculated at 11.67 which is a good representative for a regular berm or single slope. The mean of soil mechanical properties has been representative of a medium soil (SC-MC-ML-MH-GC) that has considerable affluence on most of railway or roading projects.

The Pearson correlation method has been used to find the rate of the importance for effective parameters on FOS considering the achieved result obtained the numerical analysis. On the basis of FOS that was obtained from finite element analysis, the analytical-statistical studies have been performed. Results show that the variation of FOS was mainly depended on slope height, slope angle and the additional cohesion of the surface layers of the soil. It is observed that the maximum dependency on FOS has been related to the inclination and slope height. According to the results of additional cohesion technic, it is illustrated that the surface layers of soil have more considerable effects on the FOS compare with the deeper layer. In addition, achieved result shows that the dependency effect of soil elastic modulus, cohesion and internal friction angle on the FOS have relatively the same effect.

Other correlation control considering the group effects on the FOS has been carried out and it is plotted as a dendrogram in Figure 8. The obtained results show that the group of slope height and inclination have the major effect on the FOS. Also, the group of internal friction angle, soil specific weight and elastic modulus have been considered as the second effective group on the FOS. Furthermore, the set of layer's additional cohesion and Poisson ratio have been seen as the last effective group on the FOS. There is no considerable difference between the set of layer's cohesion effects and internal friction angle.

3.3 Developing the new relationship

The input parameters to estimate FOS and to develop a new practical relationship have been chosen from the results obtained by FEM and analytical-statistical Pearson correlations (Table 5). To decrease the input parameters and compacting the developed relationship, the effect of L4 has been ignored. The L4 has no considerable correlation with FOS and its effect has been neglected. Also, the additional layer cohesion has been placed instead of the direct soil cohesion parameter. The linear regression technic is used to estimate FOS by using the selected inputs. Equation 2 has been developed by using the mentioned inputs and method to estimate FOS for rooted slopes considering slope's vegetated coverage, soil property and its geometry effects.

$$FOS_{Vegetated} = 6.053 - 0.04\alpha - 0.021\,Height - 0.041\emptyset + 0.025L_1 + 0.2L_2 - 0.072L_3 - 0.123\gamma \quad (2)$$

Table 5 Results of Pearson correlation due to achieved results of finite element models

		FOS	α	Height	Ø	C	L1	L2	L3	L4	ɣ	Elastic Modulus	Ʊ
FOS	Correlation Coefficient	1	-,858	-,259	-,206	,206	,230	,226	,223	,217	-0.094	-,206	,206`
	Sig. (2-tailed)		0	0	0.006	0.006	0.002	0.002	0.003	0.003	0.208	0.006	0.006
α	Correlation Coefficient		1	0	0	0	0	0	0	0	0	0	0
	Sig. (2-tailed)			1	1	1	1	1	1	1	1	1	1
Height	Correlation Coefficient			1	0	0	0	0	0	0	0	0	0
	Sig. (2-tailed)				1	1	1	1	1	1	1	1	1
Ø	Correlation Coefficient				1	-1,000	-,917	-,947	-,955	-,971	,500	1,000	-1,000
	Sig. (2-tailed)						0	0	0	0	0		
C	Correlation Coefficient					1	,917	,947	,955	,971	-,500	-1,000	1,000
	Sig. (2-tailed)						0	0	0	0	0		
L1	Correlation Coefficient						1	,990	,979	,960	-,501	-,917	,917
	Sig. (2-tailed)							0	0	0	0	0	0
L2	Correlation Coefficient							1	,992	,975	-,474	-,947	,947
	Sig. (2-tailed)								0	0	0	0	0
L3	Correlation Coefficient								1	,983	-,478	-,955	,955
	Sig. (2-tailed)									0	0	0	0
L4	Correlation Coefficient									1	-,486	-,971	,971
	Sig. (2-tailed)										0	0	0
ɣ	Correlation Coefficient										1	,500	-,500
	Sig. (2-tailed)											0	0
Elastic Modulus	Correlation Coefficient											1	-1,000
	Sig. (2-tailed)												
Ʊ	Correlation Coefficient											-1,000	1
	Sig. (2-tailed)												

According to result obtained by developed relationship to estimate FOS, the acceptable estimation for FOS with an emphasis on vegetated coverage effect has been calculated. The

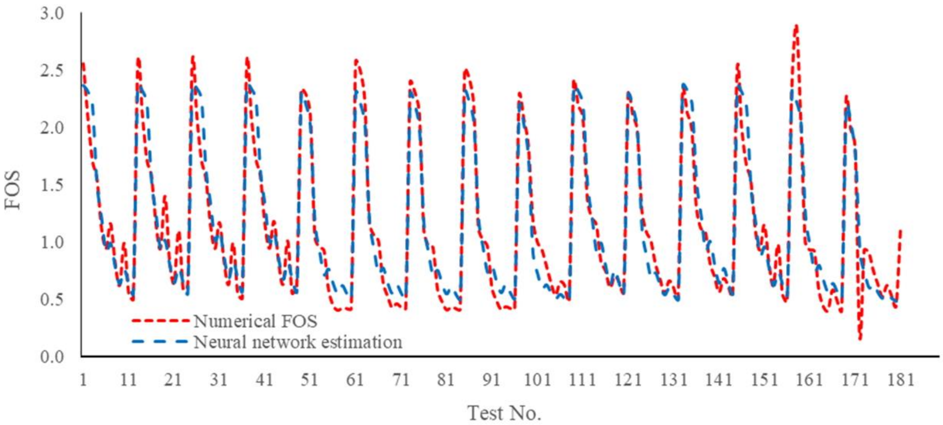

Fig. 10 Extracted results of FOS using numerical analysis and developed relationship

Table 7 The structure's information of developed multi-layer neural network to estimate the FOS for vegetated coverage slopes

Network Information			
Input Layer	Factors	1	α
		2	Height
		3	Ø
		4	C
		5	L_1
		6	L_2
		7	L_3
		8	L_4
		9	ɣ
		10	Elastic Modulus
		11	Ʋ
Hidden Layer	Number of Units		63
	Number of Hidden Layers		1
	Number of Units in Hidden Layer 1a		1
	Activation Function		Hyperbolic tangent
Output Layer	Dependent Variables	1	FOS
	Number of Units		1
	Rescaling Method for Scale Dependents		Standardized
	Activation Function		Identity
	Error Function		Sum of Squares

general R square for FOS estimation by using the proposed relationship is reported about 0.83 by using the linear regression.

The comparison results of FEM analysis and developed relationship are shown in Figure 10. Results show that the developed relationship has the acceptable estimation of FOS compare with

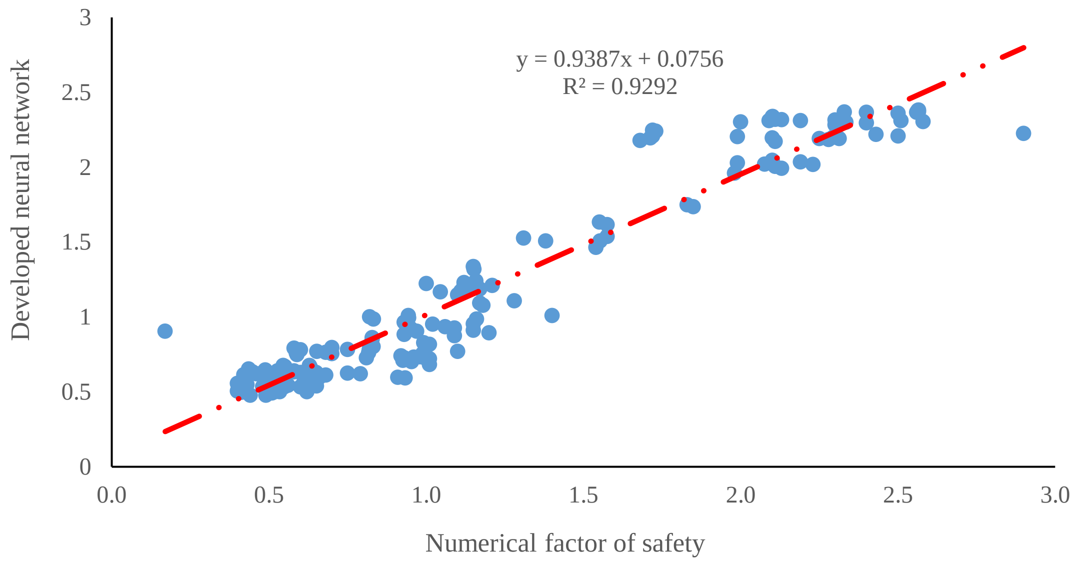

Fig. 11 Comparative results of developing multi-layer neural network FOS estimation and obtained results by numerical analysis

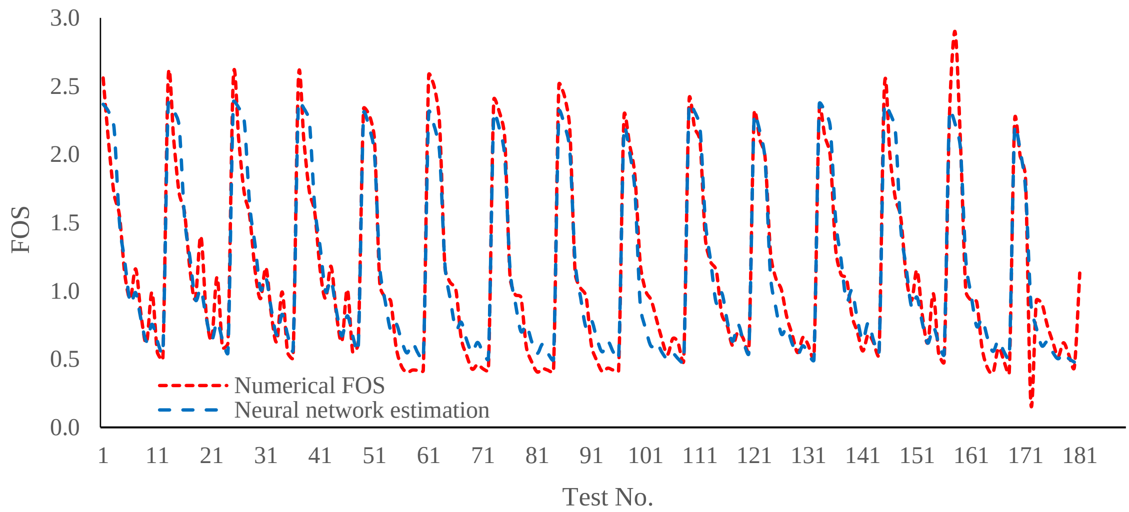

Fig. 12 Extracted results of FOS obtained by the numerical analysis and multi-layer neural network

the numerical analysis.

3.4 Result of the multi-layer neural network

To compare results of the developed relationship with an advance estimation method, a multi-layer neural network (MNN) has been generated. The main body of MNN structure is explained in Table 7. The activation function for hidden layer and output layer are used the hyperbolic tangent

Table 8 The properties for layers additional cohesion in four different categories

	Cat 1	Cat 2	Cat 3	Cat 4
L1 [kPa]	5	10	15	20
L2 [kPa]	4	7	10	16.5
L3 [kPa]	3	5	8	15.5

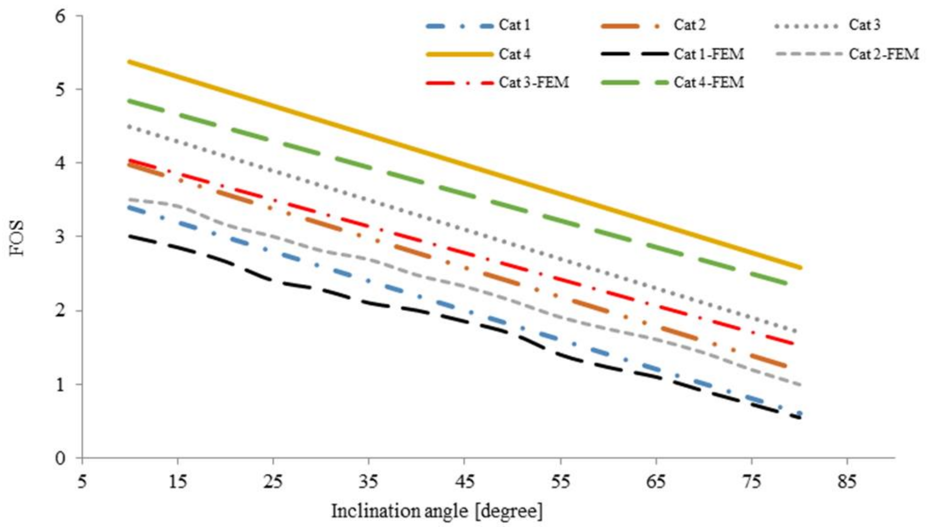

Fig. 13 Comparison results of FOS extracted from the numerical and developed relationship (H = 10 m, Ø= 22 and gamma= 15 kN/m2)

and identity respectively. In addition, 11 inputs have been considered for the developed network. In total, 180 different input data extracted from FEM analysis have been used for performance evaluation of ANN. Furthermore, 70 percent of input data are used for training step and 30 percent of remaining data are used in the test step for the developed ANN.

Results obtained by the developed MNN have been compared with results of numerical analysis. The R square for the MNN's has been obtained at 0.92. Almost 8 percent increasing has been observed compared with the result of the developed relationship. In addition, a direct linear relationship to estimate vegetated slope FOS by using ANN has been generated and it is shown in Figure 11.

The comparison results of neural network and numerical FEM are plotted in Figure 12. The maximum error of neural network observed on the value of FOS more than 2.5. Also, the result shows that on the contrary of the developed relationship's estimation the MNN has a lower estimation of FOS compare with the result of numerical FEM model.

Because there is no laboratory test the FEM method is one of the best methods for verification. Different scenario to consider the different condition of soil has been chosen for verifying the data. To verify the developed relationship four different scenario considering three different types of soil have been considered and are shown in Table 8. The first scenario has been generated for the soil with γ=15 kN/m^2 and ϕ=22º. The next one is considered with γ =18.5 kN/m^2 and ϕ = 28 degrees. The last scenario has been evaluated for the γ =21 kN/m^2 and ϕ =35º degrees.

Results of the scenarios have been shown in Figures 13 to 19.

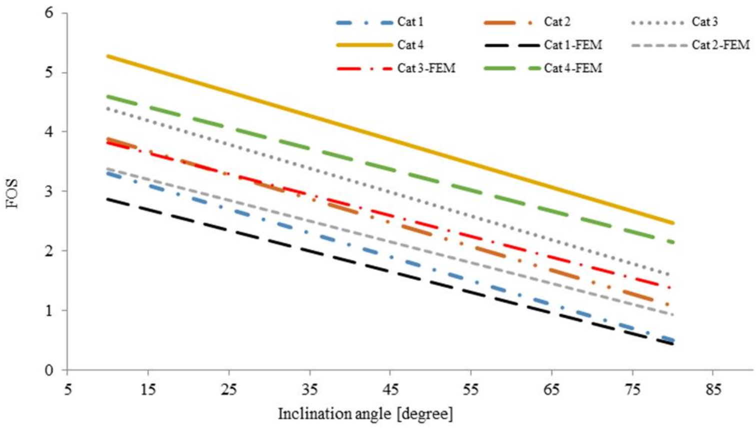

Fig. 14 Comparison results of FOS extracted from the numerical and developed relationship (H = 15 m, Ø= 22 and gamma= 15 kN/m2)

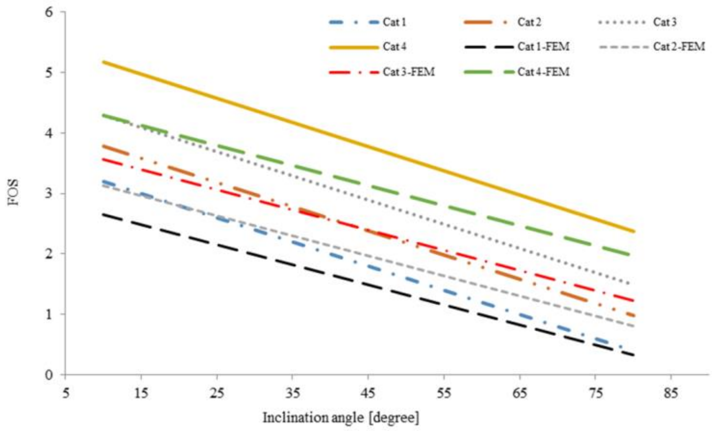

Fig. 15 Comparison results of FOS extracted from the numerical and developed relationship (H = 20 m, Ø= 22 and gamma= 15 kN/m2)

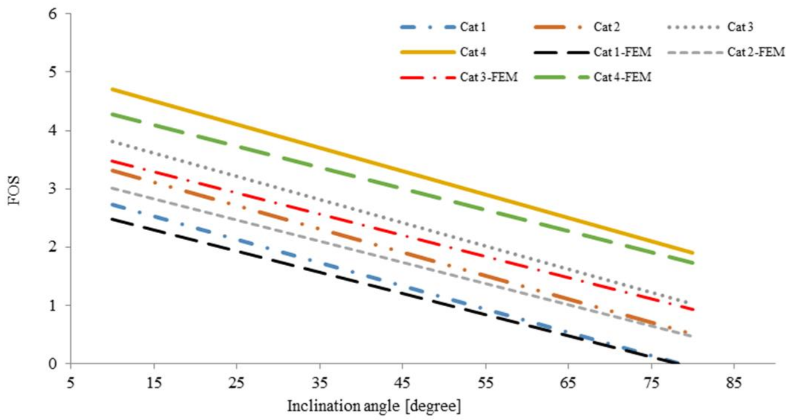

Fig. 16 Comparison results of FOS extracted from the numerical and developed relationship (H = 10 m, Ø= 28 and gamma= 18.5 kN/m2)

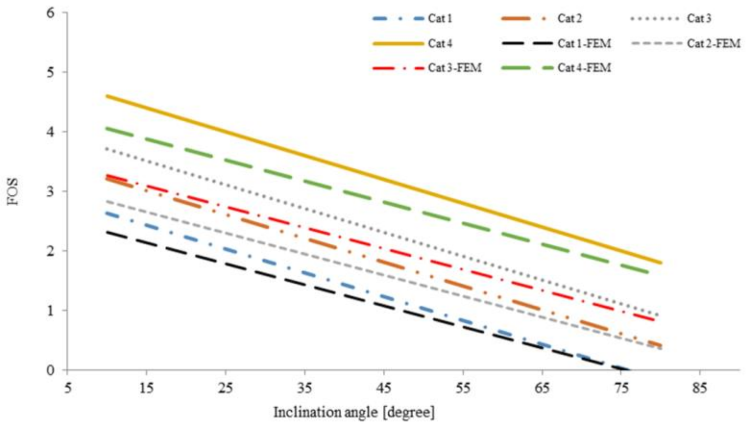

Fig. 17 Comparison results of FOS extracted from the numerical and developed relationship (H = 15 m, Ø= 28 and gamma= 18.5 kN/m2)

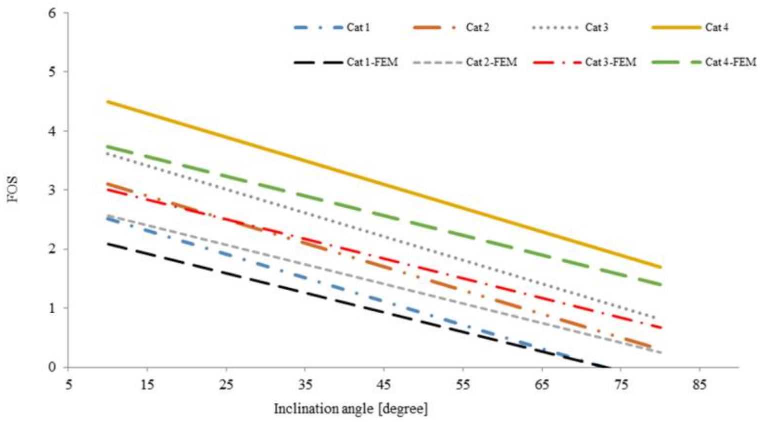

Fig. 18 Comparison results of FOS extracted from the numerical and developed relationship (H = 20 m, Ø= 28 and gamma= 18.5 kN/m2)

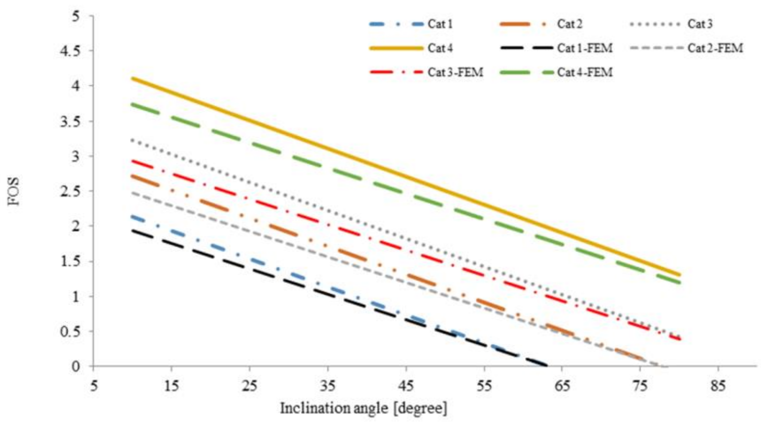

Fig. 19 Comparison results of FOS extracted from the numerical and developed relationship (H = 10 m, Ø= 35 and gamma= 21 kN/m2)

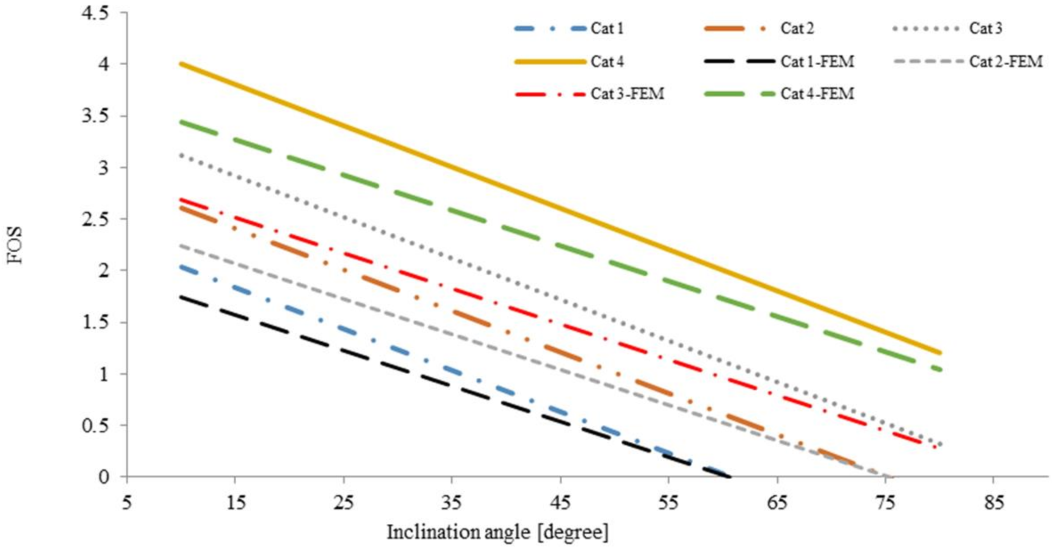

Fig. 20 Comparison results of FOS extracted from the numerical and developed relationship (H = 15 m, Ø= 35 and gamma= 21 kN/m2)

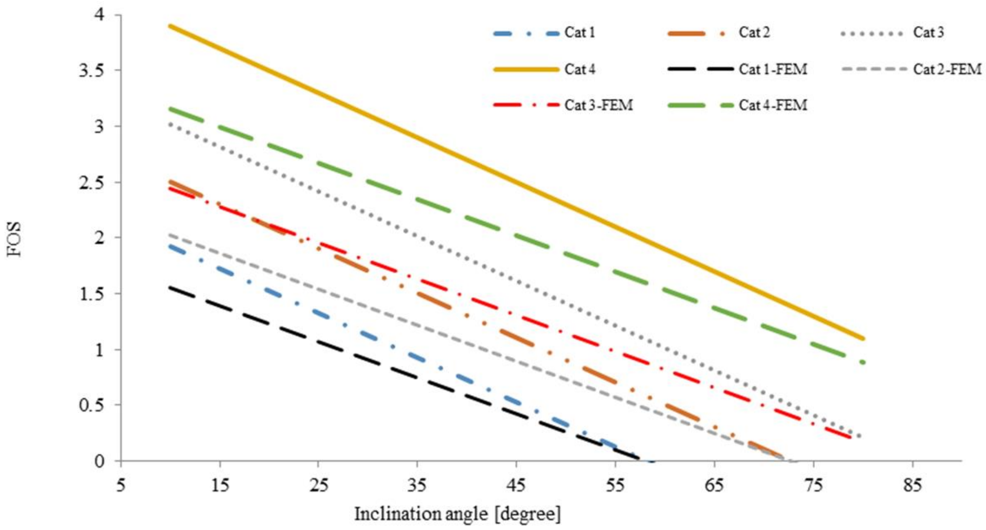

Fig. 21 Comparison results of FOS extracted from the numerical and developed relationship (H = 20 m, Ø= 35 and gamma= 21 kN/m2)

The complete analysis of the FOS has shown a relative increase obtained by presence of roots in the soil. The bare slopes with higher values of the inclination are initially unsafe (more than 30º). However, surface roots skins can increase the FOS up to 30 percent. The extracted result from FEM analysis showed that the failure mechanism for different soil types considering different root types has also different. Furthermore, it is observed that maximum effect of failure mechanism is related to the soil type and type of the roots. In addition, the mentioned effect is presented as the depth of failure or length on failure wedge.

Numerical analysis results have illustrated that the geometry condition has a considerable influence on the FOS. By using a curve fitting a probabilistic relationship between FOS and slope angle with meaningful correlation had been developed. An important observation related to slope angle also showed that slopes with the inclination less than 30 degrees are generally safe.

4. Conclusion

Evaluation for the effect of four different type of roots skin on the three different types of soil considering a variety of slope geometry by using the 2D-finite element analysis has been carried out in the current study. Thanks to the results of the numerical analysis, a new relationship to estimate the FOS considering the effects of geometry, soil strength parameters and roots coverage has been developed. Also, a new multi-layer neural network structure to estimate the FOS has generated to compare with the numerical results. The following conclusions has presented in this study:

- The maximum effect of vegetated coverage has been illustrated in case of the 45-degree angle slopes and it is estimated upper 10 percent. However, considering the slope's degree less than 30 degrees the vegetated coverage effects has been obtained less than 8 percent.
- Sand is the more influenced to improve the FOS by using the different types of roots compare with other types of soils.
- The depth of sliding will be increased based on the slope's coverage type. However, the depth of sliding will be decreased respectively considering the silty-sand, clay and sand. Results of clay have shown that the sliding will be started from the base of the slope. While other cases have shown that sliding will start from the middle of slope surface.
- Slope angle and the FOS have a nonlinear relationship with an emphasis on the slope height. It is observed that the inclination can improve the FOS 85 percent probably. While the slope height might change the FOS maximum 37 percent considering vegetated slope stabilization.
- Result of additional cohesion method has shown that the surface layers cohesion has more effects compare with deep layers. Hence the fourth layer has the lowest effect on increasing the FOS.
- The developed relationship has shown the acceptable estimation of FOS. Furthermore, the general achieved R square from the developed relationship has been reported around 0.82. However, the R square in case of safer slopes such as FOS more than 1 has been reported near 0.90. The obtained results show that there is no limitation for the type of the soil, but a limitation for inclination should be considered between 15 to 75 degrees.
- Achieved result of the MNN to estimate the FOS has shown that the suggested structure for the MNN by using hyperbolic tangent and identify a function for hidden layer and output layer respectively has been able to make an acceptable estimation for FOS. Hence, maximum achieved R square of the developed neural network has also reported around 0.95.

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