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Slope Stability Analysis Using Probabilistic Method and FEM

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***Abstract*:** *This paper deals with the analysis of a slope, located in Vlora Bypass, in Albania, using probabilistic method and finite elements method by means of Plaxis 2D. The numerical model presented in this paper is based on the results of laboratory tests, carried out in many samples, in order to determine the physical and mechanical properties of soils. The simulation of this slope allows to determine the failure surface and the corresponding factor of safety. In the end, a comparison between the values of the factors of safety calculated by each method will be presented. Also, based on results of this work, will be shown that the finite elements method has more advantages than the probabilistic method, because it enables slope failure to seek out the most critical mechanism.*

Keywords: *slope stability, factor of safety, failure surface.*

1. Introduction

Slope stability analysis is an important and challenging issue of geotechnical engineering. Damages caused by slope stability problems require detailed study of soil behaviour, by in situ site investigation and accurate laboratory tests.

Analytical methods of slope stability analysis and monitoring methods are improved lately. Through these methods and recent developments, the slope stability analysis process is more accurate, because the experience and engineering judgments, which are still considered as primary important part of analysis are well combined with rational methods, in order to improve the accuracy level, which should be achieved by systematic monitoring, continuing testing and complex analysis.

Despite the fact that all the methods used can comply the soil behaviour, it is important to know that these are half empirical methods. Given that, the real soil conditions are different, we shall rely more in site investigations data.

This paper aims to deal with the comparison of factors of safety assessed by using Probability Based Design Method (PBDM) and Finite Elements Method (FEM). The FEM analysis is performed by using PLAXIS 2D. The analysed slope is located in km 11+450, part of Vlora Bypass, in south west of Albania and a longitudinal cross section of it is presented in Figure 1.

From the drillings carried out in site, until 30 m of depth, four different soil layers are met. The layers of soil met below the ground surface, are described as follows:

Layer 1: Top soil; brown soft to firm CLAY to silty CLAY (0.00-0.60 m);

Layer 2: Brown to beige firm silty CLAY to clayey SILT. This layer is unstable and it moves in the direction of elevation drop (0.60-1.70 m);

Layer 3: Beige to grey stiff to very stiff MUDSTONE with lots of discontinuities and poor cementation (1.70-6.10 m);

Layer 4: Grey hard MUDSTONE with discontinuities and medium cementations (6.10-30.00 m).[1]

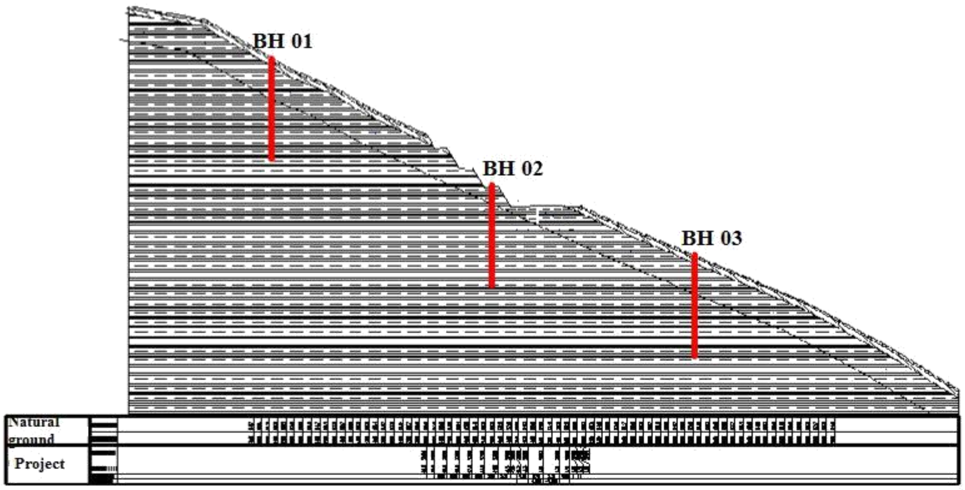

Fig. 1: Geological cross section at km 11+450

Some of the soil properties of the layers met in this soil profile are given in Table 1, here below: [1]

TABLE I: Soil properties

Layer	γ (kN/m^3)	φ (°)	c (kPa)	E (MPa)	ν
1	18.2	16	15	11.490	0.35
2	19.0	16	15	28.728	0.35
3	21.80	20	55	67.032	0.35
4	22.40	30	89	95.760	0.35

2. Slope Stability Analysis Using PBDM and FEM

2.1. PBDM in slope stability analysis

PBDM involves in analysis the probability of failure (P_f), which can be calculated after determining the most likely (average) value of safety factor (F_{MLV}), which is assessed by the average values of all soil parameters and the coefficient of variation (COV_F). The standard deviation and coefficient of variation of the factors of safety are calculated by Equations 1 and 2 given below: [2]

$$\sigma_F = \sqrt{\left(\frac{\Delta F_1}{2}\right)^2 + \left(\frac{\Delta F_2}{2}\right)^2 + \dots + \left(\frac{\Delta F_n}{2}\right)^2} \tag{1}$$

$$COV_F = \frac{\sigma_F}{F_{MLV}} \tag{2}$$

Factors of safety F^+ and F^- are calculated by varying one by one the average values of soil parameters, by plus/minus one standard deviation ($+\sigma/-\sigma$), which are given in Table 2a,b,c and d.

TABLE II a : Results using PBDM for Layer 1

Soils' properties	Values	FS	ΔFS
φ (°)	$\varphi+\sigma_{\varphi}=17.6$	$F^{+} = 1.258$	
	$\varphi-\sigma_{\varphi}=14.4$	$F^{-} = 1.258$	0
c (kPa)	$c+\sigma_{C} = 16.5$	$F^{+} = 1.258$	
	$c-\sigma_{C} = 13.5$	$F^{-} = 1.257$	0.001
γ (kN/m^3)	$\gamma+\sigma_{\gamma}=20.02$	$F^{+}=1.255$	
	$\gamma-\sigma_{\gamma}=16.38$	$F^{-}=1.260$	0.005

TABLE II b: Results using PBDM for Layer 2

Soils' properties	Values	FS	ΔFS
φ (°)	$\varphi+\sigma_{\varphi}=17.6$	$F^{+} = 1.258$	
	$\varphi-\sigma_{\varphi}=14.4$	$F^{-} = 1.258$	0
c (kPa)	$c+\sigma_{C} = 16.5$	$F^{+} = 1.258$	
	$c-\sigma_{C} = 13.5$	$F^{-} = 1.257$	0.001
γ (kN/m^3)	$\gamma+\sigma_{\gamma}=20.90$	$F^{+}=1.243$	
	$\gamma-\sigma_{\gamma}=17.10$	$F^{-}=1.279$	0.036

TABLE II c: Results using PBDM for Layer 3

Soils' properties	Values	FS	ΔFS
φ (°)	$\varphi+\sigma_{\varphi}=22.0$	$F^{+} = 1.317$	
	$\varphi-\sigma_{\varphi}=18.0$	$F^{-} = 1.200$	0.117
c (kPa)	$c+\sigma_{C} = 60.50$	$F^{+} = 1.329$	
	$c-\sigma_{C} =49.50$	$F^{-} = 1.187$	0.142
γ (kN/m^3)	$\gamma+\sigma_{\gamma}=23.98$	$F^{+}=1.207$	
	$\gamma-\sigma_{\gamma}=19.62$	$F^{-}=1.317$	0.110

TABLE II d: Results using PBDM for Layer 4

Soils' properties	Values	FS	ΔFS
φ (°)	$\varphi+\sigma_{\varphi}=33.0$	$F^{+} = 1.258$	
	$\varphi-\sigma_{\varphi}=27.0$	$F^{-} = 1.258$	0.0
c (kPa)	$c+\sigma_{C} = 97.90$	$F^{+} = 1.258$	
	$c-\sigma_{C} =80.10$	$F^{-} = 1.258$	0.0
γ (kN/m^3)	$\gamma+\sigma_{\gamma}=24.64$	$F^{+}=1.258$	
	$\gamma-\sigma_{\gamma}=20.16$	$F^{-}=1.258$	0.0

After the calculations the following results are obtained:

$\sigma_F = 0.109$ and $COV_F = 0.086$, for $F_{MLV} = 1.258$, calculated according Janbu method, calculated by Geostudio 2004, Slope/W software, as shown in Figure 2.

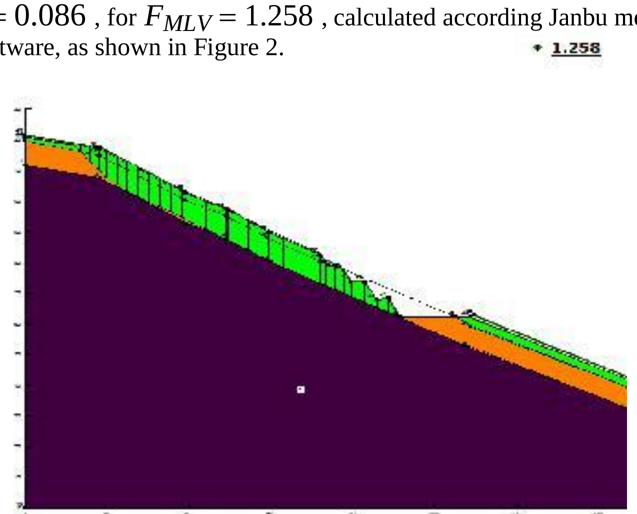

Fig. 2: Factor of safety in a non finite element analysis in Geostudio 2004, Slope/W, according Janbu method

The probability of failure corresponding to these values of F_{MLV} and COV_F is calculated referring to Duncan & Wright, based on lognormal reliability index, β_{LN} which is determined by Equation 3, as below:

$$\beta_{\ln} = \frac{\ln\left(\frac{F_{MLV}}{\sqrt{1 + COV_F^2}}\right)}{\ln(1 + COV_F^2)} \tag{3}$$

The value of $P_F = 1\%$ are determined using the Excel function NORSMDIST, by considering as input data the values of $\beta_{\ln} = 2.619$. Based on the value of the probability of failure and the variation of the factor of safety, by using the graph given in Figure 3, the factor of safety based in PBDM is estimated equal to 1.15. The factor of safety associated with the low value of probability of failure, doesn't predict any failure in this case.[3]

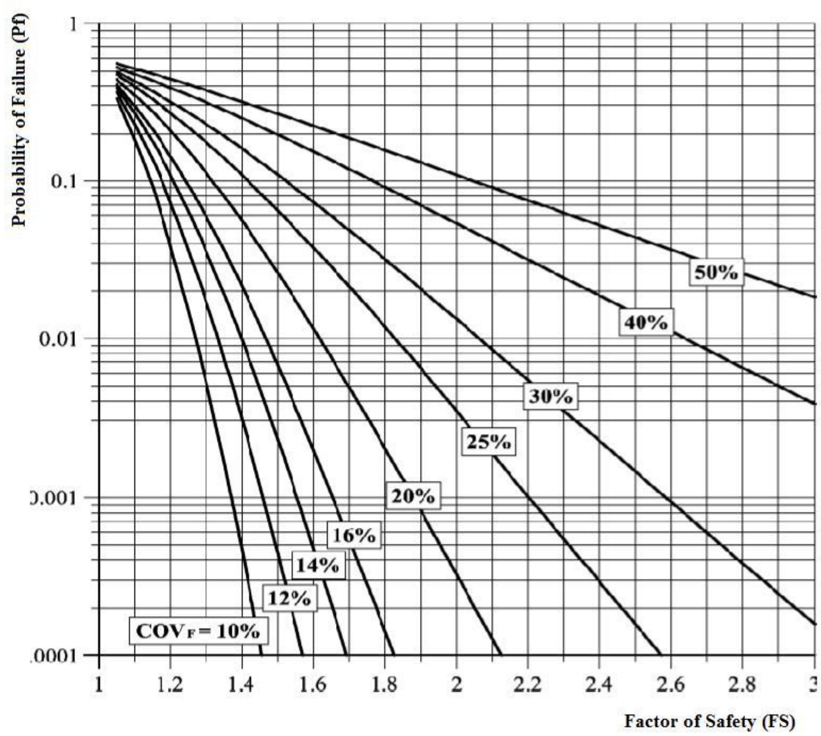

Fig. 3: Factor of safety (FS) vs. Probability of failure (P_f)

2.2. Application of FEM in Plaxis 2D

The FEM model in slope stability analysis can be used to calculate stresses, movements, pore pressures, etc, by considering the stress - strain relationship for the soil behaviour and ignoring all the assumptions done at the equilibrium methods during slope stability analysis for the failure shape or the location of the surface of failure. And also there is no assumption about the forces interacting between the slices, because the slice concept is not included in a FEM analysis.

By applying a FEM analysis in Plaxis 2D the strength reduction method is used to calculate the failure at the limit state of the equilibrium of the slope. The reduction method is based on the reduction of the internal friction angle (φ) and the cohesion (c) of soils, until the moment of slope occurrence. [4]

In Plaxis 2D the standard boundary conditions are generated automatically by the user for the bottom and one side of the model. Also the finite element mesh is generated. The analysis includes three phases: input, calculation and output. During the input phase, after adding the soil layers in the slope model, elasto - plastic Mohr - Coulomb model is applied. The soil parameters considered in this model are shown in Table 1. The strength interface is manually put as rigid. After setting the geometry model and the boundary conditions the automatic mesh was generated. The whole model is built up in different stages. Before the final calculations specific points in the slope are chosen, to get the factor of safety, FS. After running the analysis a deformed model is shown. In order to simplify the calculations, no time was set for the soft layers of clay to be consolidated. In the last stage of the calculations, the program used the sum of SF to specify the increase in strength reduction. 250 additional steps were applied during the analysis. [5]

In Figure 4 is shown the model in Plaxis 2D, after the mesh generation and the points chosen to control FS.

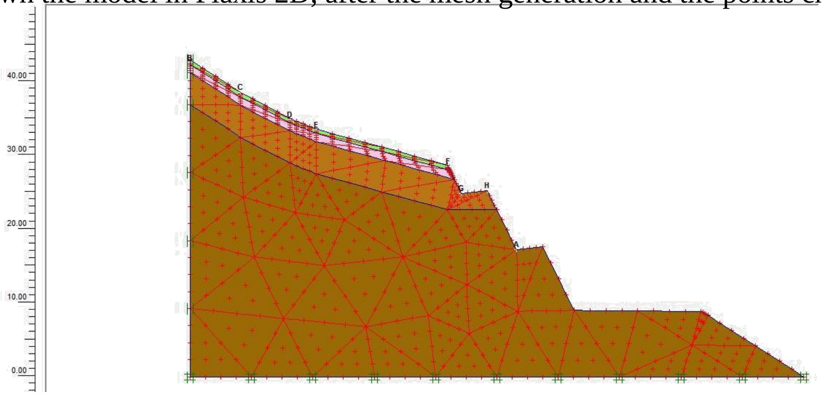

Fig. 4: Mesh generated in the slope stability model in Plaxis 2D

In Figure 5 is shown the deformed model after running the analysis.

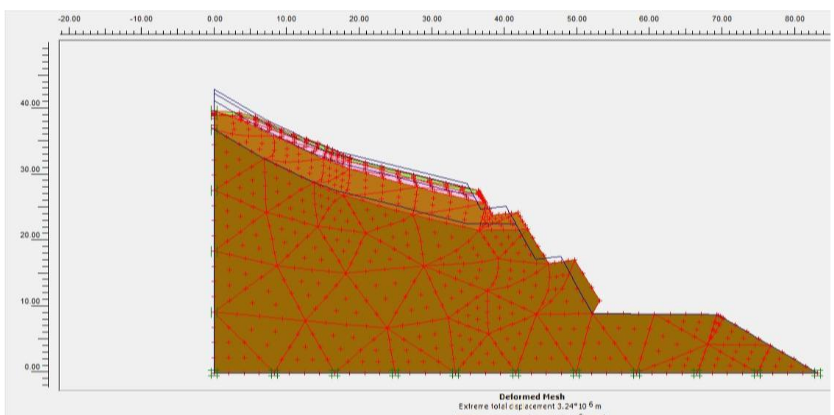

Fig. 5: Deformed model after running the analysis in Plaxis 2D

In Figure 6 a and b are shown the horizontal and total displacements.

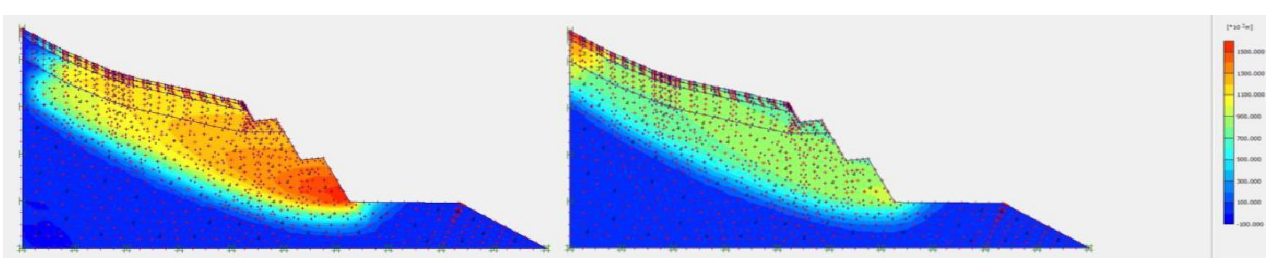

Fig. 6a, b: Horizontal and total displacements, respectively

In Figure 7 are shown the results generated by Plaxis 2D, strength reduction analysis, estimating the factor of safety for the control points chosen in the model. As shown in the graph, the minimal value of the factor of safety resulted to be FS = 1.56.

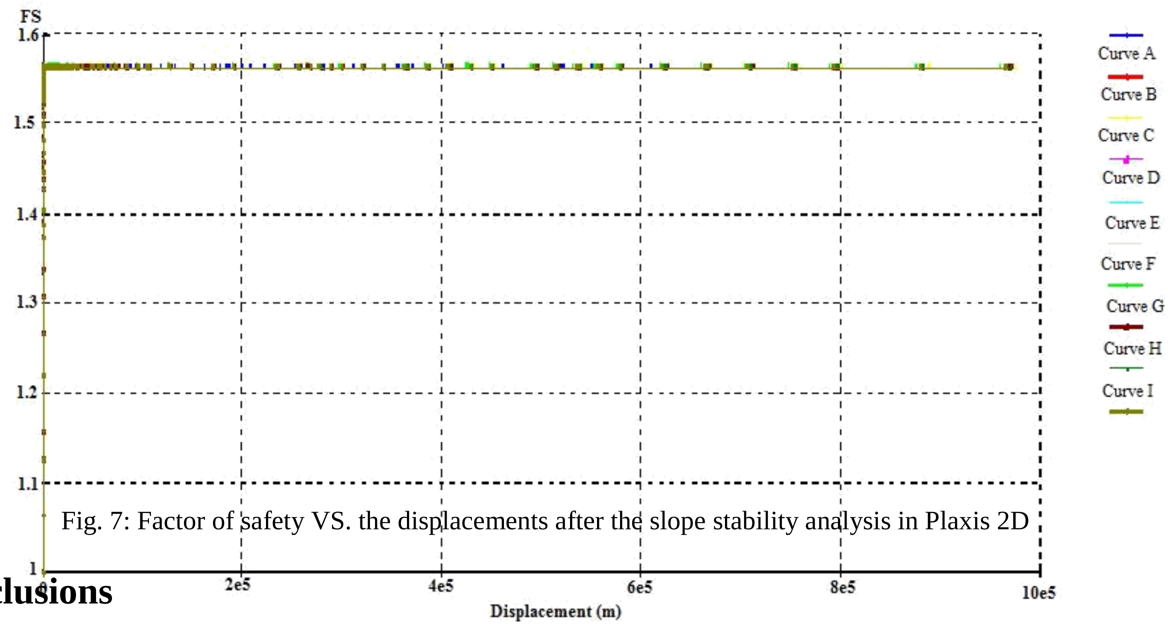

Fig. 7: Factor of safety VS. the displacements after the slope stability analysis in Plaxis 2D

3. Conclusions

According to the results presented above, the following conclusions can be mentioned:

1- The factor of safety, FS, calculated by the equilibrium methods, according to Janbu resulted equal to 1.258, which is considered also in the probabilistic approach as the most likely value of the factor of safety. The probability of failure, P_f, calculated by the probability based design method is equal to 1%, which is also the target value according to the conventional practice of slope design. Considering these results, the design of the slope is not very safe, as the value of the FS is lower than 1.30 and the value of the P_f is equal to the target value. These results put the slope out of the normal practice of safe design.

3- The factor of safety calculated by the FEM analysis is equal to 1.57. Comparing the values obtained by the slices method and the probability based method with the values obtained by the FEM analysis, the first two methods result to be more conservative. The FEM analysis, by using the strength reduction method estimates the real conditions of the soils, but in many cases the 2D analysis, by assuming the plain strain condition of the model, leads in overestimation of the soil strengths.

4- In this cases an analysis using the 3D model in FEM analysis is recommended, as a more demanding method compared with all the other methods.

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