

ANALYSIS OF SLOPE STABILITY

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Abstract

In the paper the numerical modelling of ensuring slope stability and their analysing with using of different numerical methods are presented. We have designed the cutting walls with earth nails and anchors securing for modelling of slope stability ensuring. The calculate and the mechanism of failure process of the reinforced slopes were studied using the different methods for slope stability. The nailing significantly increased the stability level for using Spencer method. The anchors increased the stability level for using Spencer method. Increasing the nail or anchors length improved the stability of the reinforced slopes. The reinforced slope exhibited a significant the stability level.

Keywords:

Slope stability;
Ensuring of slope stability;
Factor of safety;
Earth nails;
Anchors.

1 Introduction

The problem of slope stability is very topical when evaluating the stability not only of existing slopes, but also in the implementation of new slopes or excavations. The issue of slope stability is particularly important in the construction of different types of engineering or industrial buildings [1]. Slovakia is a relatively mountainous country because most of the surface is occupied by the highlands. High embankments or notches must be realized especially in civil engineering constructions.

The slope face can deform, and this may lead to landsliding especially in during excavation work of natural slopes. Landslide is caused by a combination of climatic, geological, and geomorphological factors in response to triggering mechanisms (most often are heavy rain, seismicity, or human activity). Landslides also cause huge socio-economic losses due to environmental degradation. They directly affect construction, which requires the use best practices for long-term mitigation and reduction of landslide risk. In this context, knowledge of geological and geomorphological conditions and numerical modelling provide effective protection against landslides).

If no corrective work has been performed on the slope of the cut, the landslide can continue [2]. Methods of ensuring such as soil nails, retaining structures, geosynthetic reinforcement, gabions, and shotcrete are often implemented to cut slopes stability. Where there is not enough space on a slope construct, it may be used the soil nailing. The soil nailing providing the overall slope stability and reinforced soil slopes are trusted to support motorways around the globe [1-5]. In each phase of implementation ensuring of slope, the evaluation of the slope stability in the notch and the design of notch stability structures are performed [8-13].

Historically, the oldest, but still widespread methodology for assessing slope stability is evaluation according to the degree of safety. The main advantage is clarity and simplicity, given that the safety of the structure is proved by the safety factor F_s :

$$F_s = X_{pas} / X_{akt} , \quad (1)$$

where: X_{pas} are passive forces, i.e. forces that ensure the stability of slope (prevent movement), X_{akt} are active forces, i.e. forces that threatening the stability of slope (cause movement).

In the assessment slope stability according to the method of limit states reduction coefficients be used. If the values of soil properties c , ϕ , γ have been adjusted by reduction coefficients γ_m , it is sufficient to demonstrate in the calculation and evaluation of slope stability values greater than 1 ($F_s > 1.0$). The reliability must be higher than 1,5 ($F_s > 1,5$) if characteristic values are used in the calculation. For optimal and safe design of slopes, it is also important to identify the geometry of the slope, the type of rocks and their properties.

Several methods are currently being applied to calculate slope stability problems based on the assumption that the developed slip surface is circular. If the ground is formed by rock, it is known, that method of generating the polygonal slip surface is appropriated. There are currently several methods for the calculating of slope stability [3-5].

2 Input data and methods

We analysed the ensuring and the realization of new excavations near the engineering buildings. By geological survey were determined the engineering-geological conditions. Engineering-geological conditions are represented by Quaternary sediments and the subsoil forms a Paleogene-aluminum-complex. In this area dominate Deluvial clays and Proluvial-deluvial clays formed mainly by clays of medium plasticity of consistent-soft consistence - Cl,t group F6.

The bedrock is represented by the Paleogene silty-clayey complex. They are represent siltstones and claystones that are completely weathered to weathered (have the character F6 - CL,p) and siltstones and claystones that are slightly weathered and healthy (have the character of more consistent half-rocks R4-R5). Ground water level has not been found. The parameters of rocks are shown in the Table 1.

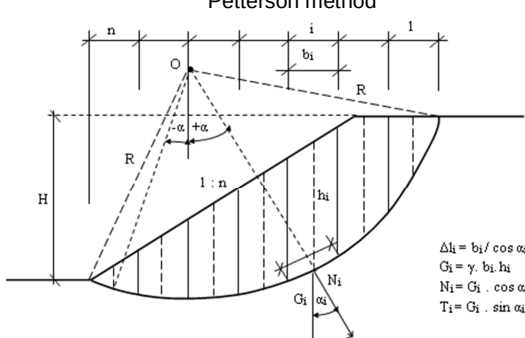
Table 1: Input data – soil parameters.

Rock characteristic	ϕ_{ef} [°]	c_{ef} [kPa]	γ [kNm ⁻³]	u
R4 - Siltstones and claystones, slightly weathered and healthy	35.0	15.0	24.0	0.3
R6 - Siltstones and claystones, weathered, (have the character F6 - CL,p)	26.0	20.0	21.5	0.35
R6 - Siltstones and claystones, completely weathered, (have the character F6- CL,p)	24.0	12.0	21.0	0.4
F6 - Deluvial clays (Cl,t)	24.0	10.0	20.5	0.4

In this study we are calculated factor of safety using two basic principles. The first principle is an assumption that the developed slip surface is polygonal (Sarima and Spencer Method) and the second principle is that the slip surface is circular (Petterson and Bishop Methods) [7,8].

The assumptions and comparisons of limit equilibrium methods are listed in the Table.2.

Table 2: Using method - assumption.

Method	Assumptions
Petterson method  $\Delta l_i = b_i / \cos \alpha_i$ $G_i = \gamma \cdot b_i \cdot h_i$ $N_i = G_i \cdot \cos \alpha_i$ $T_i = G_i \cdot \sin \alpha_i$	The sliding material (soil or rock) above the circular slip surface is divided by several vertical slices. The forces acting on each slice are calculated from their own weight and the weight of other parameters. It is the method of slices that does not take into account the action of neighbouring elements. Is the oldest and simplest method of analysing slope stability.

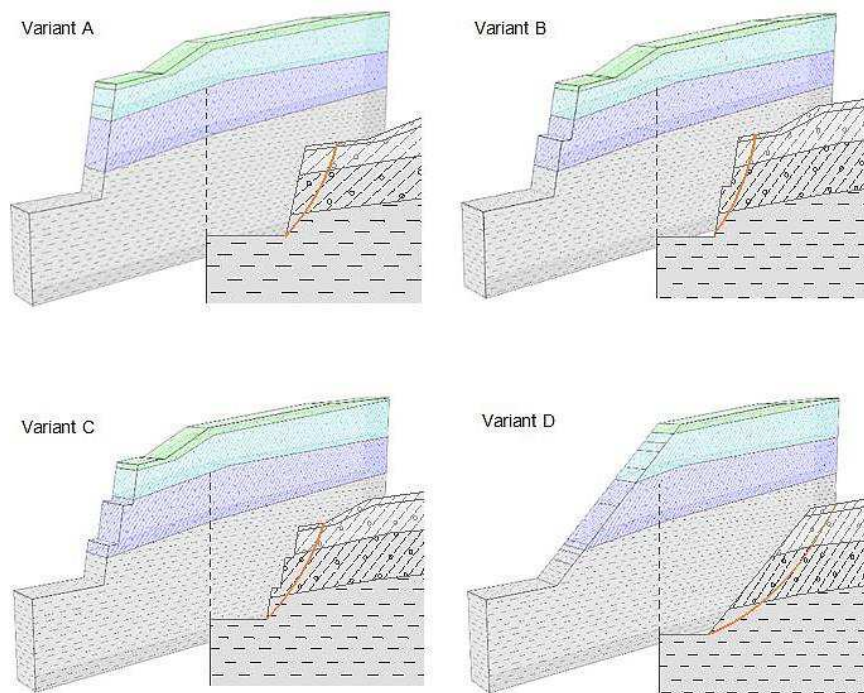


Fig. 1: The proposed notch in Variants A to D. The critical sliding surfaces (red line) obtained by the Bishop method.

We are designed the notch with earth nails and anchors securing (Variant E), for modelling of slope stability ensuring. Due to big height of the cut wall have been proposed several phases of the realization to ensure the slope stability (Variant E-1 to Variant E-5). Assessment of the slope stability was performed during each implementation phase, Fig. 2.

First variant (Variant A) - propose notch was in the gradient 5:1. The calculated safety factors do not give satisfactory results for Variant A (as can be seen from the Table 3), for which reason the Variant B - notch in the inclination 5:1 with one slope bench the width 1.0 m was suggested. The factors of safety calculated for Variant B are also unsatisfactory so Variant C, was proposed. Variant C is the notch in the inclination 5:1, with two slope benches the width 1.0 m. Variant D - proposed notch is in the gradient 1:1.25, because the factors of safety calculated for the Variant C are also unsatisfactory, Table 3.

Table 3: The safety factors for considered variants.

Methods	Factor of safety F_s			
	Variant A	Variant B	Variant C	Variant D
Petterson	0.72	0.79	0.87	1.29
Bishop	0.72	0.79	0.87	1.31
Sarma	0.76	0.83	0.93	1.36
Spencer	0.77	0.81	0.91	1.40

Variant D is satisfactory, see Table 3. This variant occupies a large area, and it means a large volume of earthwork, so we propose Variant E. Variant E - notch was designed with earth nails and anchors. This variant was proposed for modelling of ensuring of slope stability. Variant E considers the gradual realization of the cut of slope after each step Variant E-1 to Variant E-5, Fig. 2.

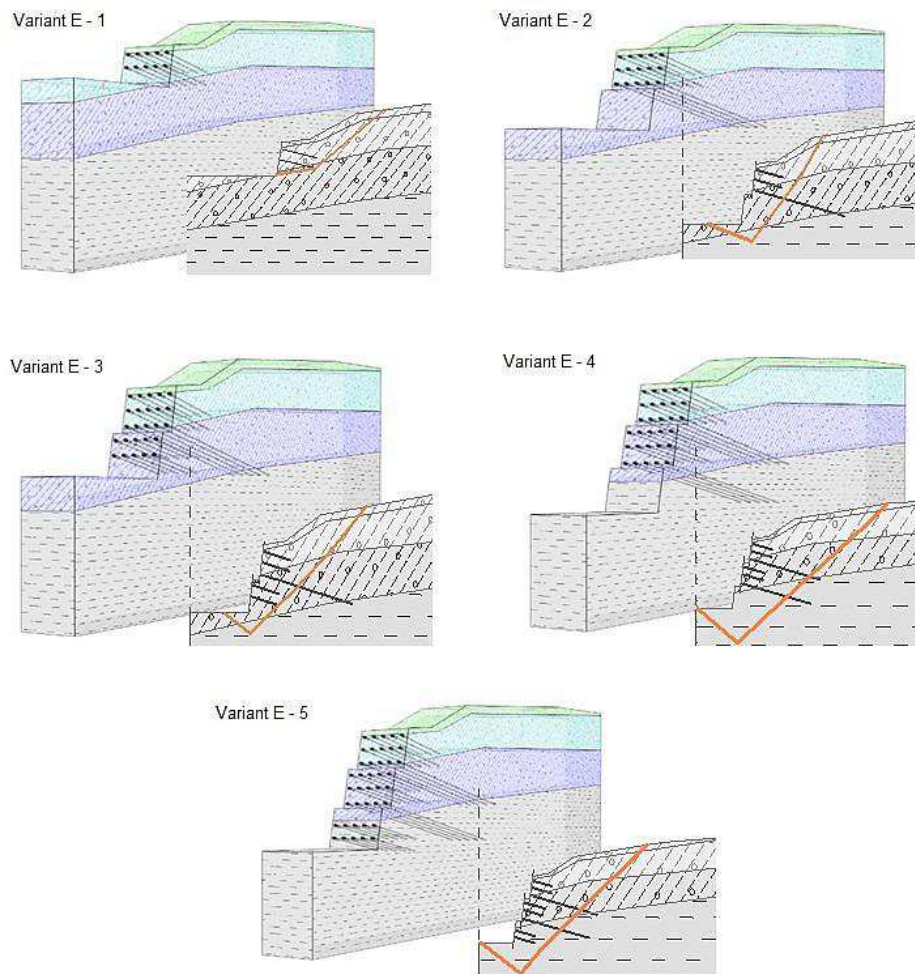


Fig. 2: The proposed notch in Variants E-1 to Variant E-5.

The critical sliding surfaces (red line) obtained by the Sarma method.

In Variant E-1, the excavation of the soil is 4m high and the slope is secured by two rows of nails with force of 120 kN and a length of 6m (nails are inclined from the horizontal axis of 11°). Before starting the second excavation, it was necessary to ensure the first excavation with anchors (20 m long) with an initial force of 750 kN (Variant E-2).

The Variant E-3 is representation of two more rows of soil nails 6 m long with force 120 kN. The installation of 20 m long anchors with a force of 750 kN and another excavation of 4.5 m height represent the Variant E-4. In the last Variant E-5, two more rows of nails were added.

The calculated factors of safety for the gradual realization of the cut of slope (Variant E-1 to Variant E-5) are shown in the table below, Table 4. The determined result values of factor of safety are shown in the following figures.

Table 4: The safety factors for considered variants.

Methods	Factor of safety F_s				
	Variant E-1	Variant E-2	Variant E-3	Variant E-4	Variant E-5
Petterson	1.81	1.95	1.95	2.15	2.16
Bishop	1.88	2.02	2.02	2.34	2.38
Sarma	1.98	2.65	2.71	3.49	3.54
Spencer	1.92	2.02	2.37	2.38	2.57

4 Discussion

The main idea of the numerical experiment is to compare the methods of slope stability and the proposed variants of notch stability solution.

4.1 Comparison of proposed variants of notch stability solution

The calculations and their results documents in Fig. 3, that variants A to C present an increased risk of landslide. The safety factors calculated are unsatisfactory for variants A to C. Variant D, in which a notch in a gradient of 1: 1.25 was proposed, satisfies the slope stability assessment. If we compare variants without ensuring of slope stability (Variant A to Variant D), Variant D gives the highest safety factors for all methods used for calculation of the problem.

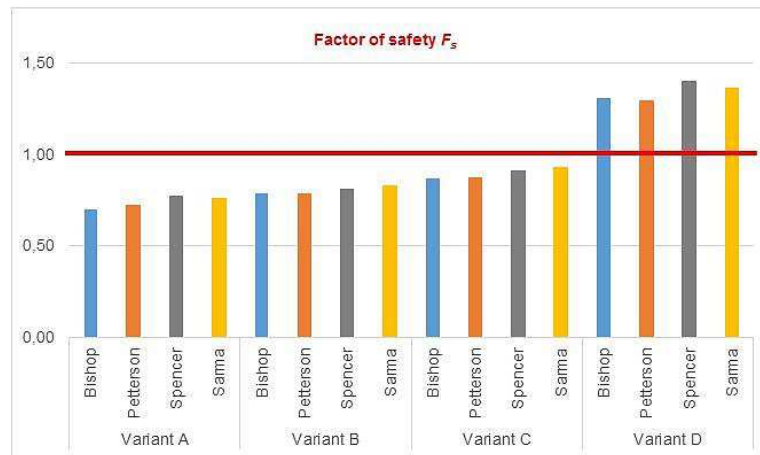


Fig. 3: Calculated safety factors for Variants A to Variant D.

The safety factor is defined as the ratio of active and passive forces. If the safety factor is in the range 0 to 1.0, the slope is unstable and a value above 1.0 means that the slope is considered stable. It can be seen in Fig. 3 that for variant A to variant C the slope is unstable. Variant D has an F_s greater than 1 and thus the cut slope is stable.

For further ensuring of slope stability Variant E, the securing of the notch was designed with earth nails and anchors. To improve the stability of the slope, it is possible to use the reinforced of the slope with nails and ground anchors. Ground anchors can also be used as a remedial measure when sliding slope. The calculated safety factors for the gradual realization of the cut of slope (Variant E-1 to Variant E-5) have the value above 1.0 indicating that the slope is stable for all step of realization, Fig. 4.

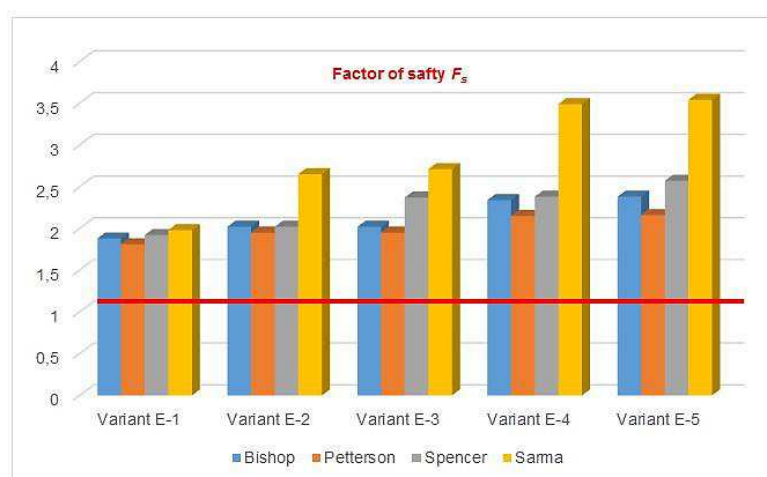


Fig. 4: Calculated safety factors for Variants E-1 to Variant E-5.

First variant (Variant A) - the proposed notch was in the gradient 5:1. The safety factors calculated for Variant A are not satisfactory (as can be seen from the Table 3), so the Variant B was proposed. The safety factors calculated for the Variant B are also unsatisfactory and we proposed Variant C. Variant D was designed due to unsatisfactory Variant C, Table 3. Variant D has the greatest factors of safety for all used calculation methods.

Variant D is satisfactory, but this variant occupies a large area, so we designed Variant E. This variant was to model the ensuring of slope stability (using earth nails and anchors). Variant E - Securing the cutting walls with earth nails and anchors. Variant E which considers the gradual realization of cut slope after each step (Variant E-1 to Variant E-5) did satisfy the assessment of slope stability. The calculated safety factors mean that the Variant E gives the highest safety factors for all calculation methods, Fig. 4.

4.2 Comparison of slope stability methods

The stability analysis considers two principles. One is the principle that the developed slip surface is polygonal for Spencer and Sarma Methods and the other assumption is that the slip surface is circular for Bishop and Petterson Methods.

Fig. 5 shows relatively good agreement of the safety factor for the used calculated methods that consider the shear polygonal surface, as well as the circular shear surface. The difference between values of the calculated factors of safety using these methods is only 0.06, Fig. 5 and Table 3.

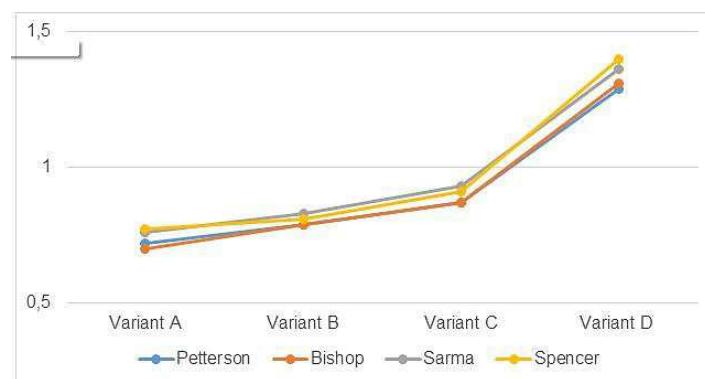


Fig. 5: Comparison of slope stability methods (Variant A to Variant D).

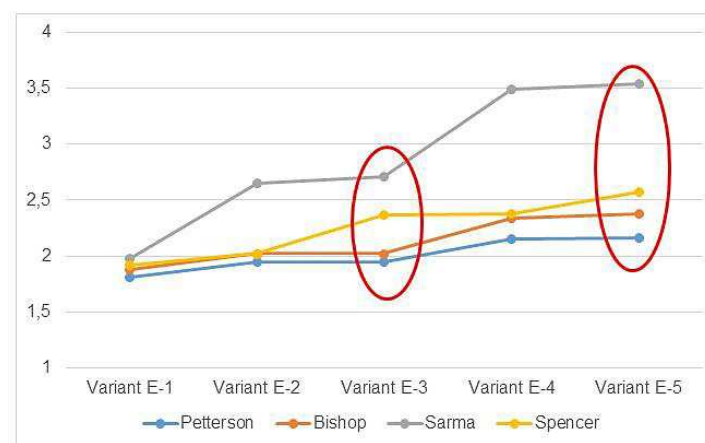


Fig. 6: Comparison of slope stability methods (Variant E-1 to Variant E-5).

The calculated factors of stability using methods that consider circular shear surface for Variant E shows relatively good agreement, Fig. 6. The difference between values of calculated degrees of stability using these methods is in the range 0.08 to 0.12, Table 3.

For Variant E, the calculated safety factors are different for methods that consider the shear polygonal surface (Sarma and Spencer). These methods show considerable differences in the calculated factors of stability, especially in steps 2, 4 and 5. In Variant E step 2, it was proposed to install anchors, in step 3 to install two more rows of nails and in step 4 to install another row of anchors. Thus, it can be assumed that a greater increase in the degree of stability will be just in steps 2 and 4, as seen by the calculated degree of stability using the Sarma method.

It follows that for the design and assessment of the slope stability formed by rocks and secured with nails and anchors is Sarma method more appropriate, i.e. the method which takes into account the polygonal shear surface when calculating.

5 Conclusions

The problem of slope stability is applicable and very actual in assessing of the stability not only of existing slopes, but also in the implementation of new slopes or excavations. The issue of slope stability is particularly important in the construction of engineering buildings, such as embankments, road cut and excavations. Roads are considered as important structures and therefore a slope stability assessment is performed for their safe and economical design. The slope face can deform, and this may lead to landsliding especially in during excavation work of natural slopes. Landslide is caused by a combination of geological, geomorphological, and climatic factors in response to triggering mechanisms.

Landslides also cause directly affect construction, which requires a use best practices to ensuring of slope stability. The calculation of slope stability of road notch was realized in several Variants (Variant A to Variant E) in this paper. In these variants we analysed the possibilities to ensuring and improving the slope stability during their realization. The slope stability was assessed by the factor of safety, to determine how close the slope is to a soil failure (landslide). The factor of safety was calculated according to generated critical sliding surfaces using various methods (Pettersen, Bishop, Sarma and Spencer).

According to the methodology and the geological conditions (the slope is formed of rocks groups R4 to R6), under which this assessment was performed, it was concluded that the Sarma method is more appropriate with regards to the calculation of the safety factor.

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