Stability Analysis of Landslide on the R1 Expressway by Limit Equilibrium and Finite Element Methods

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Abstract. The most difficult problem by designing the superior infrastructure is tracing the expressways and highways in an environment of Quaternary and Neogene complexes of fine-grained cohesive and non-cohesive soils. At the last time the typical examples are stability problems on the R1 Nitra - Tekovské Nemce Expressway. The article is focused on the description of reasons of stability loss in the deep earth cut in the 79,000 km of expressway R1, the course of the landslide, slide correction and especially slope-stability assessment before and after the occurrence of slope failures by limit equilibrium and finite elements methods by comparing the behaviour of the slope in the various model situations.

1. Introduction
In order to present a various approach to the problem of assessing slope behaviour that was exposed to the impact of the landslide activity, we chose a typical example of the landslide which is formatted in frequent geological conditions in Slovakia. The slope fault occurred in the km 79,000 km of the R1 Expressway in the section Beladice - Tekovské Nemce. In this section, the route leads through deep earth cut with a height of up to 13 m. Three years after the completion and the operation of expressway without any problem in that section, there occurred a massive landslide in November 2014, in which 6000 m³ of soil collapsed to the level of the road which was in full operation at that time. The slide correction works were completed in 2015 year

2. Geological conditions in area
The earth cut in which the fault occurred is placed in the neogenous complexes represented by the volkovské layers created by sand and gravel. Layers of incoherent soils are intersected by layers of clay [14]. The earth cut was constructed with a slope angle of 1: 2.5 with bench. No groundwater level (GWL) was observed during the construction work. Additionally, there was drainage rill constructed with depth of 1.5 to 2 m, filled by material of fraction 32/63. The drainage rill was completed in March 2014, [12].

3. Slope stability decrease of Earth Cut
3.1. The emergence of landslide
The massive landslide occurred on November 10/ 2014 with a surface area of 40 m x 80 m. The slope breaking is located on the earth cut crown near the new constructed drainage (Figure.1). The toe of landslide has stopped on the roadside of expressway (Figure 2). According the classification of slope movements [17] it was rotational landslide on rotational slip surface, active. The depth of slip surface had a variable range, from 1m on the edge of landslide to 4-6m in the middle, [12].
3.2 Slide correction
As a part of emergency measures, the slipping soil has been removed and drainage beside the road repaired. Within the final remediation measures, the slope was adjusted to a 1: 2.5. The crushed stone cover with fraction of 63/125mm has a protective function and the waterproofing foil is deposited under this stone layer to raise the water to the trench. As a preventive measure, the drainage ribs of width 0.80m and 2.0m deep, filled with crushed stone with deposited waterproofing foil has been made in the intact part of the earth cut.

3.3 Analysis of causes of landslide
The spring and summer months of 2014, the period following the realization of the drainage above the slope, were characterized by relatively frequent and heavy rainfall. The most pronounced precipitations were recorded in July and August, which, on a nationwide scale, appeared to be abnormal with a total of 168%. It has the greatest influence on the slope stability conditions. The precipitation water accumulated in the earth cut body and were subsidized from the newly built deep drainage by the water flowing from the higher-pitched areas [12].

4. The Slope Stability Assessment by Calculation Methods
Within a wide range of methods, two basic types of methods can be earmarked for practice. The analytical and numerical methods. The analytical methods are based on the limit equilibrium principles, which are determined by the safety factor (SF). This is defined as the ratio between passive - resistant forces which expression is soil cohesion and active (tangential) forces. The first analytical solutions are the works of Pettersson and Hultin (1916), which are considered the oldest method of slices with a circular slip-plane. Theoretically was the method worked up by Fellenius (1926). The essence of the method is to divide the sliding mass into the slices without mutual influence. Since this method could in some cases generate a miscalculation, in further the methods in which the interactions between the slices have been defined. These include the methods of Bishop (1954), Janbu (1954), Morgenstern and Price (1965), Spencer (1967), Sarma (1973) and others.

The second large group of stability methods are numerical methods. Currently is the most widespread the finite element method (FEM). The first authors with the approximation approach to the problem solution were Hrennikoff (1941), Courant (1943), Levy (1953), Argyris (1954, 1957). Hrennikoff”s work divides the area through the grid while Courant’s access divides the area into the final amount of triangular elements. The solution of elliptic partial differential equations of the second degree was followed. The development of FEM began in the 50s of the 20th century at the University of Stuttgart by J. Argyrysis and continued at the University of Berkeley by R. W. Clough in the 1960s. At the end of the 60s, NASA had developed NASTRAN software that worked on the FEM principle. In our area
we can be mentioned the works of Bittnar, Z., Šejnoha, J. (1992), J. Brožovský, A. Materna (2012) and the others.

This article is focused on deformation and stability analysis of the earth cut on which the fault occurred. The slope was assessed by limiting equilibrium methods (LEM) and finite elements methods (FEM) using the GEO5 and PLAXIS software. The classic Mohr - Coulomb model, expressing elasto-perfect plastic behaviour of the soil was used. The material parameters are shown in Table 1.

Table 1. The material parameters of soil

| Soil                     | γ  | γsat | qref | c ref | kref | ν  | E def |
|--------------------------|----|------|------|-------|------|----|-------|
| Additional load layer    | 19 | 19   | 35   | 0     | 5.00E-03 | 0.25 | 80    |
| Roadway body             | 22 | 22   | 20   | 200   | 9.00E-10 | 0.25 | 150   |
| Quaternary gravel G3     | 19 | 19.5 | 28   | 0     | 5.00E-03 | 0.25 | 70    |
| Neogenous sand S-F, SM   | 20 | 20.5 | 27   | 5     | 2.00E-05 | 0.32 | 30    |
| Neogenous gravel G-F, GM | 19.5| 20  | 35   | 5     | 5.00E-04 | 0.25 | 100   |
| Neogenous clay CH – soft | 21 | 21.5 | 10   | 2     | 3.00E-11 | 0.4  | 6     |
| Neogenous clay CH        | 21 | 21.5 | 17   | 11    | 3.00E-11 | 0.4  | 15    |

4.1. The calculation by Limit equilibrium methods
Slope stability calculation by limit equilibrium methods was performed in the GEO5 software, with the Slope Stability module, always for the circular and polygonal slip surface.

In general, the earth body is considered stable when the safety factor is SF > 1. According the Slovak standard STN 73 6101 "Road and Motorway Design", minimum required safety factor Fs for earth cuts is SFmin = 1,5 in cohesive soil and SF min = 1,2 in non-cohesive soils. The computation was made for the slope without construction and for the state after the construction of the earth cut. In the computation phase after the earth cut construction it was modelled the situation with a tensile crack (the new drainage) in the area above the cut and the situation with the worsen parameters - the increase of the pore pressure, the reduction of cohesive soil parameters due to the effect of water and the state with ground water level (GWL). The simplified geometric shapes – cross-section of the layers were constructed based on outputs of the detailed geological survey [14]. The computation has always been made for the permanent design situation, the polygonal slip surface has been optimized. Seismic effects have not been taken into account in the computation. The shape of the slip surface was considered to be real with regard to the occurrence of both cohesive and non-cohesive soils. Summarized results of stability analyses are in table 2.

The computation was performed for the following situations:

- Slope stability computation before earth cutting - calculation was performed for natural slope and without groundwater level influence with soils in natural state for permanent design situation.
- Slope stability computation after the earth cut was made - the calculation was made for the slope with built-in cut, without groundwater level and without a tensile crack.
- Slope stability computation after construction with the tensile crack with depth of 2 m. The cohesion c in the disturbed (failure) zone is considered to 0 kPa. The design situation is permanent, without ground water.
- Slope stability computation with earth cut and with increase of pore pressure to 30 kPa in sand layers above the clay layer (the slip surface).
- Slope stability computation with the ground water level in depth of 2.5m. The design situation is permanent.
- Slope stability computation – shear strength reduction - In the final phase, reduced parameters of clay have been included in the calculation due to water saturation. The design situation is permanent.
Table 2. Summarized results of stability analysis by LE methods using the GEO5 software

| method       | Safety factor without earth cut | Safety factor with earth cut | Safety factor with tension crack | Safety factor with increased pore pressure | Safety factor with ground water level 2.5 m | Safety factor with φ- c reduction |
|--------------|---------------------------------|-------------------------------|---------------------------------|------------------------------------------|------------------------------------------|---------------------------------|
| Bishop       | 3.22                            | 1.61                          | 1.04                            | 0.99                                     | 1.34                                     | 1.06                            |
| Petterson    | 3.09                            | 1.51                          | 1.03                            | 0.94                                     | 1.26                                     | 1.01                            |
| Spencer      | 3.21                            | 1.59                          | 1.04                            | -                                        | 1.33                                     | 1.05                            |
| Janbu        | 3.21                            | 1.59                          | 1.04                            | -                                        | 1.33                                     | 1.06                            |
| Morgenstern-Price | 3.21                          | 1.58                          | 1.04                            | -                                        | 1.32                                     | 1.05                            |
| Sarma        | 3.18                            | 1.63                          | 1.10                            | 1.06                                     | 1.38                                     | 1.09                            |

Table 2 illustrates the fact that the SF is satisfactory in all cases when assessing the slope situation in the original state without the excavation of the earth cut and after excavation with absence of GWL. By design situation with the tension crack which was modelled due to drainage on the crown of earth cut as well as an increased groundwater table that led to a decrease in the φ and c, parameters the SF was achieved, with one exception, as insufficient. All these results are a confirmation that the reason of the fault, was the external impact on the slope with the consequence of the decrease of soil parameters.

4.2 The Finite elements method - stability analysis in PLAXIS 2D

The stability analysis in this article is defined in the PLAXIS environment as a "phi-c reduction method", which means that the shear strength parameters are proportionally reduced until a steady state is reached [19]. The safety factor (SF) in this method is calculated using the Mohr-Coulomb criterion as:

\[
SF = \frac{c + \sigma\cdot \tan \phi}{c + \sigma\cdot \tan \phi_c} = \frac{c}{c_c} = \frac{\phi}{\phi_c}
\]  

(1)

Subscript c indicates that these are critical parameters and \( \sigma' \) is the effective stress [8]. The shear strength parameters of the soils with critical stresses with reduced parameters are compared. The function of plasticity \( f(\sigma) \) and the plastic potential \( g(\sigma) \) is for Mohr – Coulomb failure criterion in two dimensional problem defined as:

\[
f(\sigma) = \tau - (c\cdot \cot \phi + \sigma)\cdot \sin \phi
\]  

(2)

\[
g(\sigma) = \tau - \sigma\cdot \sin \psi
\]  

(3)

For the calculation, the Mohr-Coulomb material model was used, in FEM method it was defined by equations for the plasticity function \( f(\sigma) \) and the plastic potential \( g(\sigma) \). Parameters required for calculation are shown in table. 1. The failure criterion is written in form of:

\[
\tau = c + \sigma'\cdot \tan \phi
\]  

(4)

This is the straight line equation. Mohr - Coulomb's model is defined as a linear elastic - perfectly plastic, it is elastic managed until the failure is reached, the plastic behaviour is reached after the failure, which means that the tension remains constant and the transformation increases. The model has a defined elasticity modulus \( E \) as one (not different for small strain, initial loading/unloading). The scheme of the Mohr-Coulomb model diagram is shown in Figure 3.
The basis for the computation was the cross section, which was chosen because it passes through the places where the geological survey was done at the centre of the slope. It made possible to compare the results and to correctly modelling the individual layers. The assessment process took place in several phases. It was the SF compared with the development of deformations at selected, critical points (A, B, C, D, and E) of the profile (Figure 4).

The development of the SF depends on the calculation step (100 calculation steps), as well as the course of the deformations (60 calculation steps). After the SF stabilization, the deformations at the selected points reached the area of unrealistic values. Stability analysis took place in the natural slope phase (Figure 5), the slope with built-in earth cut (Figure 6, 7 and Figure 8), the slope with a groundwater level at 2.50m (Figure 9 and Figure 10) and the phase with the weakened layer of clay considered (Figure 11 and Figure 12). Effective parameters are used.

**Figure 3.** The working diagram for MC model, [19]

**Figure 4.** Selected points in the cross profile

**Figure 5.** Geometry of the slope – material composition
Figure 6. Geometry with the earth cut

The computation after the earth cut completion – stability calculation, Phase 2 deformation are reset.

Figure 7. Graph of SF development

Figure 8. Deformation and SF
The value of SF was stabilized before the 20th calculation step along with the deformations on the heel and edge of the crown. SF is suitable.

**The computation of SF after the earth cut completion with the ground water table in the depth of 2.5 m – Phase 3 with GWL**

![Graph of SF development and the development of deformation at selected points](image)

**Figure 9.** Graph of SF development and the development of deformation at selected points

![Deformation and SF deformation development](image)

**Figure 10.** Deformation and SF deformation development

The SF is stable around the 30th computation step, as well as deformations. The achieved SF is not satisfactory.

**The computation of SF after the earth cut completion – considered weak soft clay layer**, the calculation is based on two-phase with -reduced parameters of clay (phi-c reduction).
The SF computed by FEM method is not enough secure; with phi-c reduction it oscillates around value of 1.05. Deformation behind the crown is steady, the SF is convenient. Summarized results of stability analyses are in Table 3.

Table 3. The results of stability analyses in PLAXIS 2D software

| Method | The safety factor after the earth cut completion | The safety factor with the GWT in depth of 2.5m | The safety factor with phi-c reduction |
|--------|-----------------------------------------------|-----------------------------------------------|---------------------------------------|
| FEM    | 1.72                                          | 1.32                                          | 1.05                                  |

5. Results and discussions

The calculations were carried out according to the principles of the Mohr-Coulomb model. The material parameters obtained by the detailed engineering and geological survey were introduced into the calculations (Table 1). Stability was assessed for the slope design without intervention, slope with...
earth cut, in analytical methods with a considered tensile crack and increased pore pressure, and both methods with GWT and weakened layer with of reduced parameters. The SF has been determined to be satisfactory only for the slope situation with the natural slope and slope with the earth cut. If the tension crack (drainage), GWT and reduced strength parameters of the weakened clay zone entered in the computation, the reached SF was evaluated as unsatisfactory.

Is worth the attention the value of SF by the computation for the original condition and the condition after the earth cut construction condition, which is almost the same in both cases (except the Petterson LEM method). The value of SF after impact on the crown of the earth cut is unsatisfactory, while the value of SF determined by the FEM method being lower than for the analytical methods.

Interesting results show the graphs of the SF development and deformation at selected points of the cross section, depending on the calculation steps in the FEM. In the phases after the earth cut completion, without the impact of unfavourable conditions, the development of the SF and deformations has a certain regularity. It means that the points on the heel and crown of the earth cut appear to be relatively stable. If a weakened slip surface with reduced strength characteristics is included in the computation, the development of SF is unsteady and the deformation values reach the unlikely area until about 40th computation step.

6. Conclusions
The aim of the present article is to assess the stability conditions in the earth cut of expressway R1 in km 79,000, after the massive landslide, which occurred in 2014. It focuses on the characteristics of the stability imbalance caused by external influences, methods of remediation and observation of the behavior of the soil massif. The slope was analyzed by limit equilibrium and finite element methods with some interesting conclusion in soil behaviour in earth body.

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