Stability Analysis of a Road Scarp in the Carpathian Mountains and Methods of its Protection

Leslaw Zabuski 1, Jaroslaw Przewlocki 2

1 Institute of Hydro-Engineering, Polish Academy of Sciences, Kościerska 7, 80-328 Gdańsk, Poland
2 Gdańsk University of Technology, Faculty of Architecture, Narutowicza 11/12, 80-233 Gdańsk, Poland
lechu@ibwpan.gda.pl

Abstract. The purpose of the study was to analyse the stability of a road scarp endangered by a landslide and to consider some measures for its stabilization. The potential landslide could unfavourably alter the shape of the slope, thus a religious sanctuary situated above the slope. The present research has resulted in suggestions of possible protection methods, namely, drainage, soil nailing, installation of piles, supporting the scarp with a soil prism. They appear to be equally effective in improving the stability conditions. Therefore, the criteria for choosing one of them are rather arbitrary, and the choice should be made on the basis of economic considerations.

1. Introduction
Slope stability analysis is one of the most important and most difficult problems of soil mechanics. On the one hand, the loss of stability associated with the movement of huge earth masses can lead to serious and unpredictable catastrophes. On the other hand, stability is influenced by many different factors, often imprecisely defined, which means that considering it in a mathematical model may be difficult or even impossible. Still, the need to cope with landslides makes it necessary to obtain a better understanding of slopes and phenomena occurring in them, and, above all, to assess their stability. There are many generally accepted methods to assess slope stability. Over the hundred years since the publication of Coulomb’s fundamental work, about 100 methods of analysing and dimensioning of the slopes have been proposed. However, the results of analyses by these methods may differ.

A significant change in slope stability analysis took place in the 1970s, along with the growing use of computers. Since that time, many new methods have been introduced, while others have been considerably improved (e.g. finite element method, method of characteristics). In practice, however, the most commonly applied has been the limit equilibrium method (LEM), especially the different variants of the strip method, such as the well-known Bishop, Nonveiller and Morgenstern-Price methods. The limit equilibrium analysis is based on determining forces applied and strength mobilized over a trial slide surface in the soil slope. However, when using this method to analyse slopes, several computational difficulties and numerical inconsistencies may occur in locating the critical slip surface (depending on the geology) and hence in establishing a factor of safety. Recently, thanks to the development of the finite element and finite difference methods (FEM and FDM) and the computerization of calculations, it has become possible to apply the strength reduction method (SRM)
to calculate the factors of safety of slopes. In the FDM approach to slope stability analysis, which is
used for calculations in the paper [1], no assumptions need to be made about the shape or location of
the failure surface. The analysis of slopes focuses mainly on their deformation, rather than on their
stability. The SRM technique, originally proposed by Zienkiewicz in 1975 [2] and then developed by
many authors (e.g. [3]), is a computational procedure to determine the factor of safety of a slope by
reducing the shear strength of the soil until failure occurs. Reviews of slope stability assessment
methods can be found for example in [4], [5], [6], [7]. Some advantages and disadvantages of
particular methods, as well as discussion of factors influencing slope stability, are presented in the
paper [8].

An appropriate assessment of slope stability determines whether the slope is safe or endangered. If
the slope is likely to fail, it is necessary to strengthen it. There are many methods of strengthening or
protecting slopes, which can be divided into three main groups. In the first group, the slope angle is
reduced. In the second, a drainage system may be provided, to minimize the saturation of the subsoil.
The third group involves the use of retaining structures, such as retaining walls, cantilever walls,
contiguous bored piles, sheet piles, soil nailing, etc. The literature on the methods of slope
stabilization is very extensive. For example, many different methods of slope protection are described
in the books [9], [10], [11], as well as in the papers [12], [13], [14]; the use of soil nailing and piles for
slope stabilization is presented in detail in [16] and [17], respectively. The choice of the protection
method and the size of the stabilizing structures applied depend not only on environmental and
architectural considerations, but also on the costs involved.

The present paper analyses the stability of a road scarp in Zakopane. A potential landslide of the
slope could threaten a religious sanctuary situated above. Several methods of stabilizing the slope are
proposed, and numerical computations for each of them were performed using the FLAC2D software
[1]. A comparative analysis was carried out. The evaluation of the results of the analysis presented in
the paper should help in choosing the optimal protection measures. However, the choice of the
stabilization method should be based rather on economic considerations.

2. Road scarp description

The scarp analysed here is located in Zakopane (Poland), in the Carpathian Mountains. The
Carpathians, built of flysch rock masses (composed mainly of clay shales and sandstones), are
threatened by numerous landslides, developing both on natural slopes and on anthropogenic scarps.
The main cause of the landslides are the properties of the flysch rock mass, and of clay shales in
particular [18]. The weathering of these rocks transforms them into weak soft soil (clay), which is very
prone to sliding.

The high and steep scarp formed as a "shelf" for a local road (Piszczory Street) lies in a valley.
Above it, the Sanctuary of Our Lady Revealing the Miraculous Medallion is situated. At the bottom of
the valley flows the Olczyski Stream (Figure 1). The history of the sanctuary began in the first years of
the 20th century. The construction was planned already in 1913, but owing to administrative obstacles,
it did not begin until 1981 and was eventually completed in 1988. Nowadays, the sanctuary is an
important religious site, visited by numerous pilgrims.

Some years ago, signs of a landslide on the road scarp appeared, causing cracks in the asphalt layer
(Figure 2) and irregularities on the scarp surface. The recognition of the object including geological
and engineering investigations and a preliminary stability analysis [17], revealed the presence of a
slide surface in the scarp below the road. There are visible signs of shallow soil creep (inclined trees,
small cracks on the surface of the slope). It can be expected that landslide phenomena will continue to
develop under the influence of negative factors, such as the saturation of the slope during rainfall or
spring thaws and heavy road traffic. In fact, the road does not meet standard requirements. In this case,
the values of the factors of safety are slightly above 1.0. The importance of the road access to the
sanctuary was one of the reasons why stakeholders decided to stabilize the scarp to avoid possible
further damage. The methods considered included drainage, scarp nailing, piling and supporting by a
soil prism.
3. Method of stability analysis
The stability analysis was carried out by the FLAC2D software [1] based on the two-dimensional explicit Finite Difference (FD) method. In contrast to traditional “limit state” analysis, this program provides a full solution of the coupled stress/displacement, equilibrium and constitutive equations. The model is divided into FD zones forming a grid. Each zone behaves according to a prescribed stress and strain law in response to forces and boundary restraints. Calculations of the safety factor \( F \) are based on the strength reduction method ([2], [3]). The method is applied with the Mohr-Coulomb failure criterion. It is typically applied in factor-of-safety calculations by a stepwise reduction of the shear strength of the material to reach a limit equilibrium state of the slope. A series of simulations are performed using trial values of the \( F_{\text{trial}} \) factor to reduce the cohesion \( c \) and the friction angle \( \phi \). One technique to find the strength values corresponding to the failure onset is reducing or increasing incrementally the strength until a failure state is reached.
4. Geotechnical and numerical models of the landslide

4.1. Original scarp
In the present case, the "original scarp" is understood as the landslide scarp without any engineering intervention. Geotechnical and numerical models were developed for the scarp cross-section corresponding to the central axis of the landslide (see Figure 1). It can be assumed that landslide deformations in this cross-section are the most intensive. The analysis of the geological and engineering conditions in the cross-section and the results of the field inspection suggest that the area above the street is not undergoing typical landslide deformations. The main problem is the stability of the slope from the level of the road to the base of the slope. Therefore, in creating the calculation model, the possibility of a large slip in the area above the road was rejected, and the boundaries adopted in the model were the level of the road and the base of the slope, as shown in Figure 3.

![Geotechnical model used as the basis for the numerical model of the original scarp](image)

Figure 3. Geotechnical model used as the basis for the numerical model of the original scarp

Nevertheless, a landslide below the road would cause a negative change in the geometry of the entire slope, including the zone above the road level. This could result in a landslide in this zone and
threaten the church, located above the slope. The numerical model is shown in Figure 4. The parameters of the soil layers and asphalt assembled in Table 1 are given in the report [19].

![Figure 4. Numerical model of the original scarp](image)

Table 1. Parameters of the soil and asphalt in the numerical model

| Soil/asphalt    | Density $\rho$ [$\text{t/m}^3$] | Shear modulus $G$ [kPa] | Bulk modulus $K$ [kPa] | Cohesion $c$ [kPa] | Angle of friction $\phi$ [''] |
|-----------------|---------------------------------|-------------------------|-----------------------|-------------------|-------------------------------|
| Bedrock         | 2.2                             | 38462                   | 83333                 | 100               | 32                            |
| Sandy loam      | 2.1                             | 7085                    | 15352                 | 13                | 12                            |
| Embankment soil | 2.2                             | 38462                   | 83333                 | 100               | 32                            |
| Silty mud       | 1.95                            | 3820                    | 8277                  | 7.7               | 9.2                           |
| Asphalt         | 2.4                             | 96154                   | 208333                | Elastic model     |                               |

The water table was assumed in the middle position, but it can change under extreme conditions (completely dry or fully saturated scarp).

4.2. Scarp stabilization methods

Four stabilization methods were analysed:
- drainage of the scarp (completely dry mass),
- nailing of the scarp surface,
- installation of piles,
- supporting the slope with a soil prism.

Soil nails are modelled in the program as one-dimensional axial elements, which cannot sustain a bending moment. Nails are grouted along whole length and therefore develop axial forces as the grid deforms. Nails in this model have the following properties: spacing $1\text{m} \times 1\text{m}$; length $l = 3.8\text{-}5.0 \text{ m}$; diameter $d = 6 \text{ cm}$; elasticity modulus $E = 10^5 \text{ MPa}$; stiffness of the contact with the surrounding soil $K = 4.75 \times 10^4 \text{ kN/m/m}$; cohesion force of the contact with the surrounding soil $C = 800 \text{ kN}$. A cross-section of the scarp stabilized by nails is shown in Figure 5.
Figure 5. Scarp stabilization by nailing

Piles are two-dimensional elements that can transfer normal and shear forces and bending moments to the grid. Shear forces act parallel to the element, and normal forces act perpendicular to the element. Piles in the present model have the following properties: spacing $0.5 \times 0.5$ m; length $l = 5$ m; diameter $d = 30$ cm; elasticity modulus $E = 1.5 \times 10^4$ MPa; shear and normal stiffness of the contact with the surrounding soil, $K_s = 10^8$ kN/m/m and $K_n = 10^6$ kN/m/m; shear and normal cohesion force of the contact with the surrounding soil $C_s = C_n = 10^7$ kN/m; friction angle of the contact with the surrounding soil $\phi_r = 35^\circ$. The heads of the piles are connected together by a concrete cap. A cross-section of the scarp stabilized by piles and their arrangement are shown in Figures 6 and 7, respectively.

Figure 6. Scarp stabilization by piles

Figure 7. Arrangement of the piles
It is also possible to support the scarp with a soil prism 1.5-2.0 m thick, as shown in Figure 8. All proposals presented above were analysed, and safety factors were calculated for each of them. It was hoped that the results would assist in choosing the best, most effective solution.

Figure 8. Supporting the scarp with a soil prism (berm)

5. Results and discussion
The shapes of the slip surface represented by the maximum shear strain increments are similar in all cases. Therefore, only one case, the slip surface for the scarp supported by the soil prism, is shown in Figure 9. The slip develops in sandy loam along its interface with the flysch bedrock.

Figure 9. Slip zone in the scarp, represented by the maximum shear strain increments

The values of safety factors for all cases are given in Table 2.

Table 2. Safety factors calculated for all cases

| Variant                              | Figure No. | Safety Factor $F$ |
|--------------------------------------|------------|------------------|
| Original slope                       | 4          | 1.041            |
| Drained slope (dry soil mass)        | ---        | 1.146            |
| Nailed slope (6 nails in cross-section) | 5          | 1.330            |
| Piled slope                          | 6, 7       | 1.318            |
| Supported slope                      | 8          | 1.341            |
As can be seen in Table 2, only in the case of the drained slope, the safety factor does not reach the minimum value required by the Polish regulations (i.e. $F=1.30$). This means that drainage by itself, without any additional measures, does not ensure the required stability conditions. In the other three cases, the safety factor is higher than 1.30, and its value is approximately the same in each case. Therefore, the choice of the technical solution for scarp stabilization on the basis of $F$ values alone is arbitrary.

However, each of the above options has some limitations which help to choose the best one and eliminate the others. For example, the steepness of the scarp makes it difficult to use some of the methods on its surface. It seems that the installation of piles would be particularly difficult. On the other hand, legal problems can arise in connection with the property rights to the meadow below the scarp. Moreover, it may prove problematic to obtain the necessary volume of soil for the construction of the supporting prism. It is also known that the cost of nailing is usually lower than that of other conventional slope stabilizing methods [16].

6. Conclusions
The analysis presented in this paper clearly shows that a thorough stability analysis should be carried out before deciding on how to stabilize an endangered slope. However, the required safety factor of the improved structure does not allow for optimal decision regarding countermeasures. Independently on other restrictions of technical nature, economic considerations have to play a decisive role in choosing the optimal method of stabilizing the scarp. The cost of each option can be calculated to assist this choice.

References

[1] FLAC2D, "User's Manual", Itasca Inc., Minneapolis, 2000.
[2] O.C. Zienkiewicz, C. Humpheson, R.W. Lewis, "Associated and non-associated visco-plasticity in soil mechanics", Géotechnique, Vol. 25, No. 4, pp. 671-689, 1975.
[3] E. M. Dawson, W. H. Roth, A. Drescher, "Slope Stability Analysis by Strength Reduction", Géotechnique, Vol. 49, No. 6, pp. 835–840, 1999.
[4] R. Chowdhury, "Geotechnical Slope Analysis", CRS Press, Taylor and Francis Group, 2010.
[5] G.P. Giani, "Rock Slope Stability Analysis", CRS Press, Taylor and Francis Group, 1992.
[6] C.W. Duncan, "Rock Slope Engineering: Civil Applications", CRS Press, Taylor and Francis Group, 2017.
[7] J. Madej, “Methods for checking slope stability”, Wydawnictwa Komunikacji i Łączności, Warszawa, 1981, (in Polish).
[8] J. Przewłócki, "Some comments on slope stability. Part I: Deterministic analysis". Inżynieria Morska i Geotechnika, No. 2, pp. 141-149, 2004, (in Polish).
[9] D. Jarominiak, “Light retaining structures”, Wydawnictwa Komunikacji i Łączności. Warszawa 2000, (in Polish).
[10] L.W. Abramson, T.S. Lee, S. Sharma, G.M. Boyce, "Slope Stability and Stabilization Methods", 2nd edition, J.Wiley & Sons, New York, 2002.
[11] Transportation Research Board, "Cost-Effective and Sustainable Road Slope Stabilization and Erosion Control", NCHRP Synthesis 470, Washington D.C., 2012.
[12] L. Zabuski, K. Thiel, Z. Ambrożewski, "Rock Bolting as Stabilization Measure of Abutment Slides Occurring During Performance of Hydrotechnical Construction", Proc. Int. Congress on Large Dams, Florence, Q.75, R15, pp. 201-206, 1997.
[13] R.D. Holtz, R.L. Schuster, "Stabilization of Slopes", [in:] Turner A.K., Schuster R.L, Landslides Investigation and Mitigation, National Academy Press, Washington D.C, pp. 437-473, 1996.
[14] M.E. Popescu, K. Sasahara, "Engineering Measures for Landslide Disaster Mitigation", [in:] Landslide Disaster Risk Reduction, Springer Verlag, Berlin, Heidelberg, 608-631, 2009.
[15] L. Zabuski, Stabilizing of the road embankments, Zeszyty Naukowo-Techniczne Stowarzyszenia
M. Kulczykowski, J. Przewłocki, B. Konarzewska, „Application of Soil Nailing Technique for Protection and Preservation Historical Buildings” IOP Conf. Series: Materials Science and Engineering, 245, 2017.

R. Sołtysik, „Protection of slopes and road corps in landslides with the use of palisade made of DFF piles anchored with TITAN micropiles”, Zeszyty Naukowo-Techniczne Stowarzyszenia Inżynierów i Techników Komunikacji Rzeczpospolitej Polskiej, Oddział w Krakowie, No. 88, 2009, (in Polish).

L. Zabuski, A. Wójcik, E. Gil, T. Mrozek, W. Rączkowski, Landslide process in a flysch massif – case study of the Kawióry landslide, Beskid Niski Mts. (Carpathians, Poland), Geological Quarterly, Vol.53, 3, PGI, Warsaw, 317-332, 2009.

L. Zabuski, "Preliminary Analysis of the Stability of Slope in Zakopane - Piszczyory Street", Gdańsk, 2014, (internal report, in Polish).