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QUARRY STABILITY ANALYSIS FOR COMPLEX SLIP SURFACES USING THE MATHSLOPE METHOD

PETAR HRŽENJAK

University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering
Pierottijeva 6, 10000 Zagreb, Croatia

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Abstract

Due to the specific characteristics of rock mass compared to other geological materials, the calculation of rock slope stability is very complex. One of the basic characteristics of rock masses is discontinuity, which, to the most degree, is formed by the geological structure and its elements. Because of discontinuities the slip surfaces of complex shapes are formed in rock slopes, mostly of straight and curved segments.

The calculation of the stability factor of rock slopes for complex shapes of slip surfaces has been made possible by the development of the MathSlope method. The complex shape of slip surface has been achieved by introduction of planes of discontinuities in the slip surface. Thus, the setting up and searching procedure of critical slip surfaces of complex shapes is very different in the MathSlope method than in other ones.

The example of back analysis for the quarry Vukov Dol shows the successfulness in determining the critical slip surface, as well as the calculation factor of stability for the complex shape of slip surface. Apart from calculating the factor of stability for the complex slip surface, the solution for the position of discontinuity on the slope is obtained, which matches with the real position on the quarry.

Ključne riječi: Stabilnost stijenskih kosina, složene klizne plohe, MathSlope metoda, stabilnost kamenoloma

Sažetak

Proračuni stabilnosti stijenskih kosina izrazito su složeni zbog specifičnih značajki stijenske mase u odnosu na druge geološke materijale. Jedna od osnovnih značajki stijenske mase je diskontinuiranost, koju u najvećoj mjeri čine geološke strukture i njihovi elementi. Zbog prisutnosti diskontinuiteta u stijenskim se kosinama formiraju klizne plohe složenih oblika, najčešće kombinirane od ravnih i zakrivljenih segmenata.

Razvojem MathSlope metode omogućen je izračun faktora stabilnosti stijenskih kosina za složene oblike kliznih ploha. Složeni oblik klizne plohe ostvaren je uvođenjem ravnina diskontinuiteta u kliznu plohu. Pri tome se u ovoj metodi način zadavanja kao i postupak traženja kritične klizne plohe složenog oblika bitno razlikuje u odnosu na postojeće metode.

Obrađeni primjer povratne analize za kamenolom Vukov Dol pokazuje uspješnost u određivanju kritične klizne plohe kao i proračuna faktora stabilnosti za složeni oblik klizne plohe. Osim izračuna faktora stabilnosti za složenu kliznu plohu dobiveno je i rješenje za kritičan položaj diskontinuiteta na kosini koji se dobro podudara sa stvarnim položajem na kamenolomu.

Introduction

The stability of the quarry with large-scale rock slopes still presents one of the main problems in rock and mining engineering today (Sjoberg, 2001). The main cause of this is the presence of the structural elements which have a pivotal role for stability. For large-scale slopes, the structural elements of interest are major structures, such as lithological contacts, faults and large shear zones, and structural domains which consist of a few sets of discontinuities. Because of discontinuities the failure of large-scale rock slopes may involve the combination of several different failure mechanisms in which the slip surface of complex shape is formed.

The rock slope stability analysis may be divided into two groups of methods: the limit equilibrium and numerical methods. Limit equilibrium models are traditionally divided in models with structurally controlled planar or wedge slides and models with circular or near circular failure surfaces. Numerical methods of analysis used for rock slope stability may be conveniently divided into three categories: continuum, discontinuum and hybrid modelling (Stead et al., 2001). The advantage of these numerical models over the limit equilibrium models is in the calculation of the state of stress that can be used in displacement and progressive failure of models as opposed to a simple factor of safety. Because of common acceptance of the safety factor (stability factor) approach as the main criterion of slope stability, methods calculating this factor, like the limit equilibrium methods, are more often used.

Since failure of large-scale rock slopes may involve the combination of several different failure mechanisms, this type of failure cannot be modelled by means of the simple continuum or discontinuum approach or by the limit equilibrium method. Therefore, in practice, both limit equilibrium and numerical modelling tools are used together to generate a range of possible solutions for the range of input parameters that exist for a particular site. With the aim of solving the rock slope stability problems more successfully, the numerical research in developing the estimation method named MathSlope has been undertaken (Hrženjak, 2004).

The MathSlope method

The method and algorithm named MathSlope has been developed with the aim of calculating the stability factor of rock slopes for complex shapes of slip surfaces. The algorithm MathSlope has been created by the program Mathematica in the form of an added package (Hrženjak et al., 2003). The setting up and searching procedure of critical slip surface of complex shape is very different in the MathSlope method than in other ones. The setting up of the slip surface is carried out in two steps. In the first step the basic shape of the slip surface is formed, whereas in the second, with the introduction of discontinuity surfaces, the complex shapes of the slip surface are created. The basic assumption in this method is that all slip surfaces have a concave shape.

The slip surface is defined by the point of exit of the slip surface at the toe of the slope, the angle of secant and angles of deviation of slip surface from secant on top and at the toe of the slope. These angles actually define tangents to the slip surface (fig. 1).

The discontinuities can be introduced as “floating” and “positioned”. The “floating” discontinuities mean that discontinuities will be added to each slip surface at the point that has the same inclination as the inclination of the discontinuities. The discontinuities will be added to the slip surface in length of persistence that has been given as input data. The “positioned” discontinuity means that discontinuity surface will be added according to the position on the slope. The “floating” discontinuities refer to sets of discontinuities which represent structural domains, unlike the “positioned” ones, which refer to individual or major structures such as contacts, faults and shear zones.

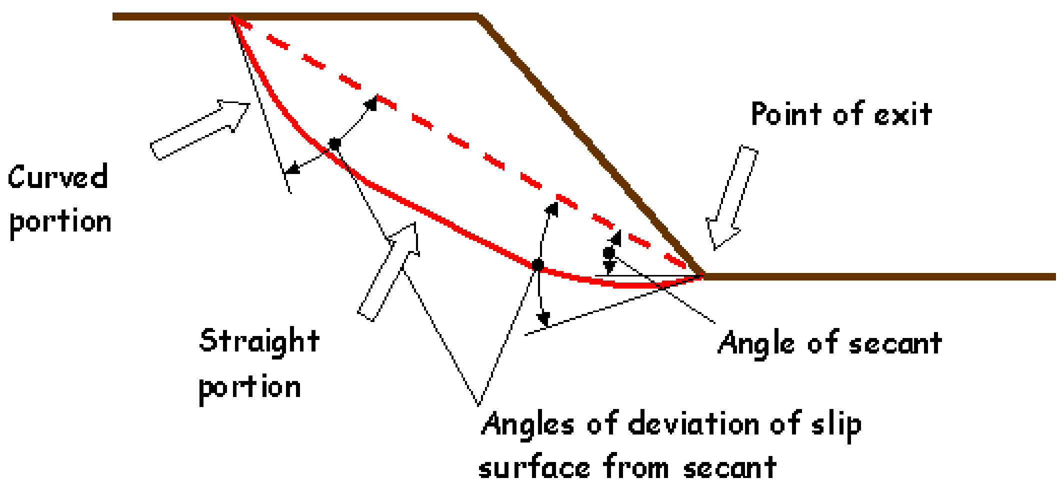

Figure 1. Setting up a complex shape of the slip surface

Slika 1. Postava klizne plohe složenog oblika

The procedure of searching for the critical slip surface can be carried out through setting up of a large number of assumed slip surfaces and the iterative method. In the first method one or more areas for the searching of a slip surface for every slope may be assigned. The area of searching comprises of the coordinates of the points on the top of the slope that assigns the range of angle deviation of the secant and point of exit of the slip surface. The shape of the slip surface starts from the straight line that actually presents the secant across different twisted shapes within theoretical possible angles of slip surface. The step of changes of all angles may be arbitrarily chosen. In this way the number of possible theoretical combinations of shapes of the slip surfaces may be generated. In the iterative method the shape and position of the slip surface is changed gradually until a minimum value of the stability factor is obtained. In combining these two procedures critical slip surface of complex shape can successfully be found. As in other methods the critical slip surface is a slip surface with the lowest factor of stability.

The stability factor, as in other methods, is defined as the ratio of the summation of the available resisting shear force (S_r) along a slip surface to the summation of the mobilized shear force along a slip surface (S_m).

$$S.F. = \frac{\sum S_r}{\sum S_m} \quad (1)$$

The normal stress (σ_n) and the mobilized shear stress (τ_m) at the point of slip surface are computed using the following equations:

$$\sigma_n = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta \quad (2)$$

$$\tau_m = \tau_{xy}\cos 2\theta - \frac{\sigma_x - \sigma_y}{2}\sin 2\theta \quad 3)$$

where σ_x and σ_y are total stresses in x and y direction respectively, τ_{xy} is shear stress and θ is an angle measured from positive x axis to the line of application of the normal stress at the point of slip surface.

The state of stress for the model must be estimated by a numerical program such as the finite element or the finite difference method. After estimation, the state of stress is introduced in the model of slope stability by a specially created function. After that, some of the interpolation functions of the program *Mathematica* are used for obtaining a continuous field of stresses.

The MathSlope algorithm consists of accessory functions such as HoekBrown and Barton, which have been created for the estimation of rock mass strength and shear strength of rock joints according to the Hoek-Brown (Hoek et al., 2002) and Barton (Barton, 1976) failure criterion respectively. The shear strength for the complex shape of the slip surface is controlled by the shear strength of rock mass at the points of curved portion and by the shear strength of discontinuity at the points of straight portion of the slip surface. In this way the Hoek-Brown failure criterion for rock mass and Barton failure criterion for discontinuity may be directly applied in the strength model of the slip surface.

Case study analysis

The quarry Vukov Dol

The quarry of marble-like limestone Vukov Dol is placed on the South-Eastern hillsides of Medvednica, about 3 km north from the place Kašina. The geological structures of the quarry are very complex because of the genetic as well as postgenetic processes. Metamorphic processes have conditioned the origin of marble-like limestone, marble and phyllite. The rock mass is subsequently intersected with many faults and joints as a result of a number of tectonic processes.

Throughout exploitation the sliding of rock mass appeared several times. The last large sliding happened 2000 when over 350.000 m^3 of material collapsed. The main cause of instabilities, as then considered, were the foliated planes with the orientation of 158/42° which, in this part of the quarry, caused the plane sliding. However, based on observation, the sliding most probably occurred along a complex slip surface, first as a plain failure along the foliated plane, and then along curved surfaces through the rock mass.

After that a number of investigation and back analysis have been made with the aim of establishing rock mass properties.

The developed forehead of land-slide is formed by a surface with the orientation of 150/70-80° and a depth of over 20 m as is obvious on picture (fig. 2) and profile (fig. 3).

Figure 2. Forehead of land-slide on the quarry Vukov Dol

Slika 2. Čelo klizišta na kamenolomu Vukov Dol

The slope stability back analysis was performed by the MathSlope algorithm using the Hoek-Brown failure criterion for rock mass and Barton failure criterion for discontinuity which have been directly applied in the strength model of the slip surface. The average properties of rock mass were estimated at: density of 2690 kg/m^3, intact uniaxial compressive strength σ_{ci}=54 MPa, constant m_i=10 and geological strength index GSI=27÷29. For the discontinuities the average value of the joint rough coefficient JRC of 7÷9 and the joint wall compressive strength JCS of 20 MPa were estimated. Figure 3 presents the comparison of slip surfaces of complex and general shapes with the slope before and after break down. The plain of discontinuity on the slip surface is marked with a dashed line.

The solution for the complex shape of the slip surface with discontinuity, in this case foliated planes, very well coincides with the real slip surface on the slope. However, it is important to notice that the solution for the general slip surface without discontinuity is also possible. Consequently, the real shape and position of the critical slip surface is most probably between these two solutions and it depends on the real values of rock mass and discontinuity properties.

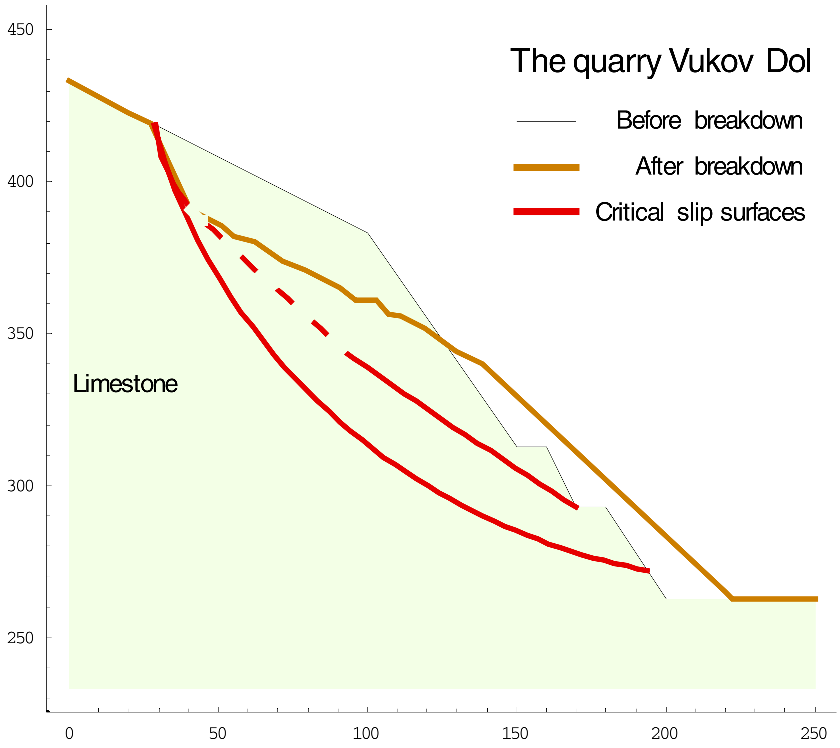

Figure 3. Profile of the quarry Vukov Dol

Slika 3. Profil kamenoloma Vukov Dol

The quarry Pregrada

The second example of the slope stability analysis for the project solution was carried out for the quarry Pregrada. The quarry Pregrada is placed in the North-West part of the Republic Croatia. The rock mass of the quarry Pregrada is mostly Triassic dolomite. The total height of the quarry amounts to about 210 m. Based on the geological characteristics of the rock mass, the quarry is divided in two regions. The first region, marked as the Dolomite I, stretches from the elevation +205 to approximately +310 m and the second region, marked as Dolomite II, stretches from +310 to +415 m. The geometry of the slope is illustrated in figs. 4 and 5 that show the 210 m high slope with fourteen 15 m high benches. The inclination of the individual bench face is 65° and the overall slope angle is about 42,6°.

Dolomite I is represented by dark grey dolomite with a density of 2769 kg/m3, GSI=49, σ_{ci}=60 MPa and m_i=11. Dolomite II is represented by light grey dolomite, light yellow lime-dolomite and dolomite breccia with a density of 2769 kg/m3, GSI=53, σ_{ci}=88 MPa and m_i=8. By the Hoek-Brown failure criterion the average cohesion of 0,679 MPa and the degree of internal friction of 26,6° for Dolomite I, as well as the average cohesion of 0,844 MPa and the degree of internal friction of 29° for Dolomite II were obtained.

The discontinuities which can influence the stability of the quarry are: discontinuity with an angle of inclination of 31°, for the first region, Dolomite I, and discontinuity with an angle of inclination of 43°, for the second region, Dolomite II. The characteristics of the first discontinuity are JRC=4÷8, JCS=32÷35 MPa and φ_b=30°. The characteristics of the second discontinuity are JRC=8÷12, JCS=82÷88 MPa and φ_b=30°. The persistence of the discontinuities varies from 20 to 30 m, but may be up to 50 m in special cases.

The slope stability analysis has been performed for a number of cases. For the first case, the stability analysis was carried out without any discontinuities and the factor of safety of 1,876 was obtained (fig. 4). For the second case, the stability analysis was carried out with discontinuities and the factor of safety of 1,854 was obtained. It is obvious that there is no significant difference in the obtained values of safety factors for these cases. This is due to the relatively good characteristics and small lengths of discontinuities, but for the reduced shear strength of discontinuities, for example, for the cohesion of 10 kPa and angle of internal friction of 17° and length of discontinuity of 50 m, the factor of stability falls to 1,576 (fig. 5).

Another important feature of these analyses is that changes of characteristics of rock mass and discontinuities, beside their influence on the safety factor, have a significant influence on the position of the critical slip surface. This is obvious from shapes of the slip surface in figs. 4 and 5.

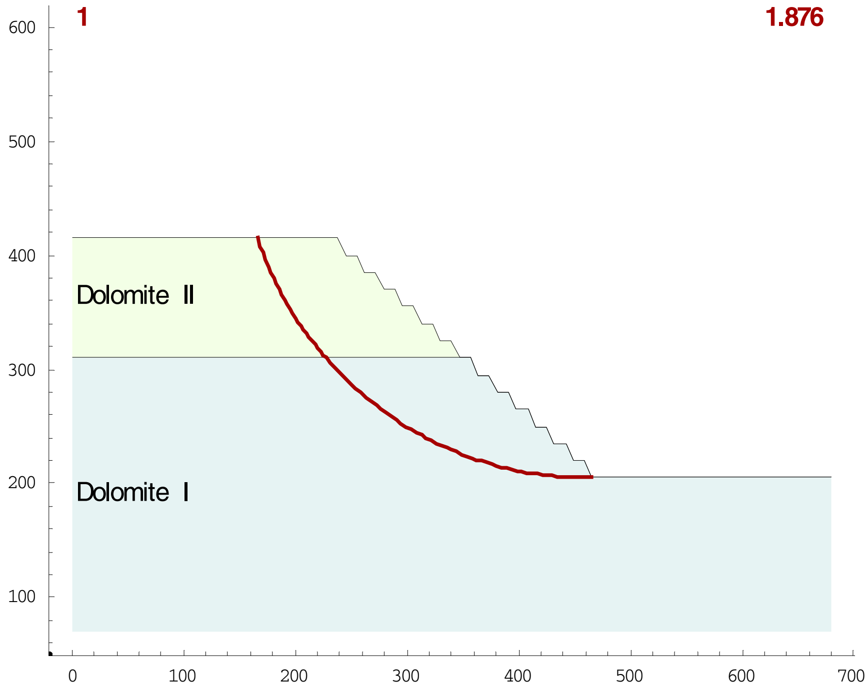

Figure 4. Solution for the slope stability analysis without discontinuity

Slika 4. Rješenje analize stabilnosti bez diskontinuiteta

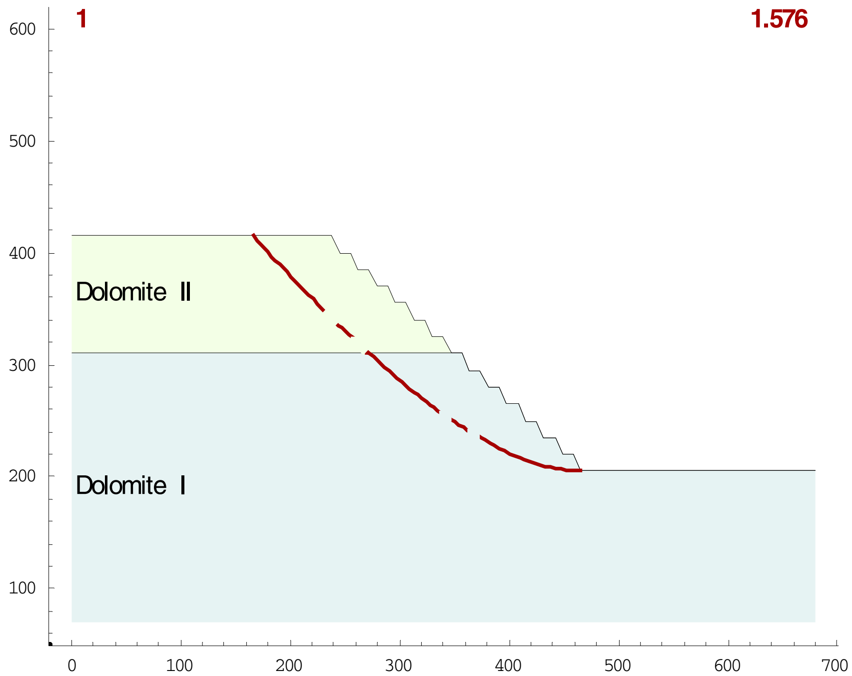

Figure 5. Solution for the slope stability analysis with discontinuities

Slika 5. Rješenje analize stabilnosti s diskontinuitetima

Conclusion

The MathSlope method has been developed with the aim of analysing the large-scale rock slope stability. The basic characteristic of the method is the calculation of the factor of stability and the search for the critical slip surface of complex shape, namely the combination of the failure through the rock mass and failure along the surface of discontinuity. The algorithm makes it possible to directly apply the Hoek-Brown and Barton's failure criterion in the method of calculation.

The analysed examples show how successful the MathSlope method is in determining the critical slip surface as well as in calculating the factor of stability for complex shapes of slip surfaces. Apart from calculating the factor of stability for complex slip surface, the solution for the position of discontinuity on slope is obtained, which coincides with the real position on the slope. The presented results show that the MathSlope method can be well applied in the procedure of quarry stability calculation, which is a good reason for the further development of the method.

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