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Contents

Three dimensional stability analysis of the "Mokra Gora" landslide

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Abstract: Stability analysis of landslides is, in fact, three-dimensional problem. This is a consequence of an unregular shape of sliding body and it is characteristic for numerous landslides in Serbia. However, till now a day, there isn't the generalized procedure of three-dimensional stability calculations which involve slip surfaces of arbitrary shape. Instead of that, it is common to make two-dimensional analysis for a most critical cross section throughout the three-dimensional sliding mass. In this paper is presented approximate method of introduction three-dimensional effects in stability calculations and, on basis of that, three-dimensional stability analysis of landslide "Mokra Gora" is performed, too. In the cases where the three-dimensional effects are considerable, their introduction in stability calculations ensure to obtain more correct findings about stability of landslides.

Keywords: landslide, stability analysis, three-dimensional effects, equivalent sliding body.

Introduction

The basic point for performing effective slope stability analysis is to formulate the right problem and to solve it correctly. It requires knowledge of geological characteristics of the terrain, shape of slip body and underground water conditions, too. In the view of that, it is known that landslides in Serbia are, in most cases, closely dependent of geological conditions of the terrain and on fact that the activity of any landslide, during long period of its development restore periodically, more or less, along pre-existing slip surface. According to that, a detailed research of each single landslide should be done. On the basis of that, its stability has to be analyzed and the remedial measures has to be determined [Lokin and Ćorić, 2000].

The necessity of the application three-dimensional slope stability analysis is based on the fact that the sliding in the terrain is realy three-dimensional. Sliding body in space has the third dimension. Therefore, any presentation of the three-dimensional phenomenon by a two-dimensional approximation is significantly simplifying the real conditions in the field. Success in geotechnical engineering practice, including evaluation how much successfully is achieved two-dimensional simplification of the three-dimensional geometry [Gitirana et al, 2008].

There is a fundamental difference in the results of the analysis of slope stability, depending on whether it is carried out a two-dimensional or three-dimensional analysis. It is well known that stability analysis performed by using 2D or 3D approach does not receive the same critical slip surface. Even for a homogeneous slope and the same sliding surface, safety factors of 2D and 3D analysis are different [Albataineh, 2006].

The difference between the results obtained by 2D and 3D stability analysis depends on the geometry of the slope, lithological heterogeneity of terrain and soil parameters.

Potentially significant differences in the results obtained by applying 2D and 3D analysis of slope stability are worth the effort to use more 3D analysis in routine geotechnical practice because use of 3D stability analysis enables more rational geotechnical design of remedial measures.

Basic assumptions of stability analysis

The analyzing of slope stability and determining the correct safety factor are, in fact, three-dimensional problems. This is a consequence of unregular shape of the sliding body and it is characteristic, especially, for many landslides in Serbia. However, till now a day, there aren't the generalized procedures of three-dimensional (3D) stability calculations which involve slip surfaces of arbitrary shape and are simple enough for use in geotechnical practice [Cheng and Yip, 2007]. Instead of that, it is common to make two-dimensional (2D) analyses and they are carried out for cross section with the minimum safety factor.

Stability analyses can be done in drained or undrained conditions. It has to be emphasized that in the natural slopes, in our geological and geotechnical conditions, sliding is the most common result of increasing the groundwater level in the rainy period and such cases have to be analyzed in drained conditions.

Stability analyses should be made by limit equilibrium methods which satisfy all conditions of equilibrium. These are following methods of slices: Janbu's, Morgestern-Price's, Spencer's, Maksimović's, Fredlund-Krahn's methods (Ćorić, 2008). In the context of limit equilibrium approach they give a value of safety factor which differs by no more than ±6 percent from what may be considered "correct" value [Duncan, 1996]. This is certainly close enough for practical purposes because slope geometry, water pressure and shear strength can seldom be determined with accuracy as good as ±6 percent. Thus, if the geotechnical engineer performs slope stability analysis using methods that satisfy all conditions of equilibrium he is justified in following:

- calculated safety factor is "correct" in terms of the mechanics of the problem and
- he can devote his attention to accurate evaluation of the properties of soils and remedial measures.

However, the question arises about the accuracy and reliability of 2D analyses to 3D problems. Research studies [Duncan and Wright, 2005] have shown clearly that factors of safety calculated using 3D analyses are larger than those calculated using 2D analyses. Implicit in this conclusion is the notation that the 2D section analyzed is the most critical section through the 3D potential sliding mass. Moreover, the difference involved in applying 2D analysis to a 3D landslide is not high. The difference in the values of the safety factor, in most cases, is less than 10% [Ćorić, 2012], but in extreme cases it ranges from 15% to 50% [Lam and Fredlund, 1993, Hadži-Niković et al, 2013].

From above it follows that 2D analyses give somewhat conservative results regarding safety factor and because of that, they provide reasonable and sufficiently accurate approach to the most practical problems of slope stability. It should be born in mind, however, that regarding the shear strength calculated from back analysis they give somewhat unconservative values i.e. they are not on the safe side. But knowing accurate value of shear strength, as much as possible, is of a great importance because it is used in calculations of landslide remedial measures [Stark and Eid, 1998]. Therefore, when the three-dimensional effects of a landslide are significant, then they should be included in the stability analysis.

Three-dimensional stability analysis by equivalent sliding body method

When lateral effects of the landslide are significant then the 2D analysis is not appropriate, because 3D effects need to be taken into account. These cases are following:

- slip surfaces are bowl-shaped or deep ones
- width of slide in the plan is less than about twice the length of slide in plan
- engineering-geological conditions and/or groundwater levels have significant changes along width of sliding mass
- shear strength of soil at lateral planes is higher than shear strength of soil along the sliding surface

There are no rigorous method available for the analysis of a generalized 3D slip mass, but there are some approximate procedures of introduction 3D effects in stability calculations [Lambe and Whitman, 1969; Skempton, 1985]. In the view of that, J. N. Hutchinson – Imperial College, London (personal communication) suggests that the slip mass has to be approximated to regular shape and for such idealized, equivalent slip mass, three-dimensional factor of safety has to be calculated. Following this idea, actual irregular slip mass has been approximated to regular sliding body (Figure 1) and two-dimensional and three-dimensional safety factors are determined.

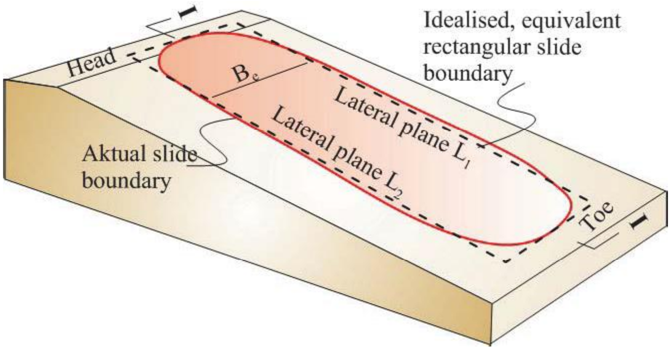

Figure 1 - Approximation of irregular slip mass to regular sliding body

The two-dimensional factor of safety F_S^{2D} on characteristic cross-section I-I:

$$F_S^{2D} = \frac{R}{D} \qquad (1)$$

where: F_S^{2D} - safety factor on cross-section I-I

R - resisting forces or moments

D - disturbing forces or moments

The three-dimensional factor of safety F_S^{3D} is given approximately by

$$F_S^{3D} = \frac{B_e{*}R + R_{L1} + R_{L2}}{B_e{*}D} = F_S^{2D} + \frac{R_{L1} + R_{L2}}{B_e{*}D} \qquad (2)$$

where:

F_S^{3D} - safety factor on the equivalent sliding body

B_e - width of equivalent sliding body

R_{L1} - resisting forces or moments on lateral plane L_1

R_{L2} - resisting forces or moments on lateral plane L_2

This method is general one in the sence that may be applied for circular or noncircular slides and in the terms of total or effective stresses. Certainly, the use of this method requires high quality of geotechnical investigations and good engineering judgment in approximation of unregular slide by the equivalent sliding body, too.

Example of three-dimensional stability analysis

In this section it will be presented approximation of landslide „Mokra Gora" to regular sliding body and calculation of safety factors FS2D and FS3D.

Landslide "Mokra Gora" is formed on a slope between local road that leads to the ethno village "Drvengrad" on Mecavnik and national road IB 28 that leads to Visegrad [Project, Highway Institute, Belgrade, 2014]. The inclination of the natural slope is between 18o and 23o. Terrain basis is formed of flysch sediments in which marly and sandy limestones, marls and rarer sandstones dominate. These cretaceous sediments (K22) are physically-chemically altered and weathered in the surface zone. Deluvial clay deposits with debris are formed over cretaceous sediments on the entire slope, thickness of 4.0 - 5.0 m.

Sliding occurs along the contact of different lithological layers. In the frontal and partly in the central parts of the landslide, sliding occurs along the contact of deluvial debris and surface weathered zone of flysch sediments, while the surface weathered zone is affected by sliding in the foot part of the landslide.

The maximum length of landslide is 135m, the width is between 40m and 65m and maximum height is about 5.5m. (Fig. 2)

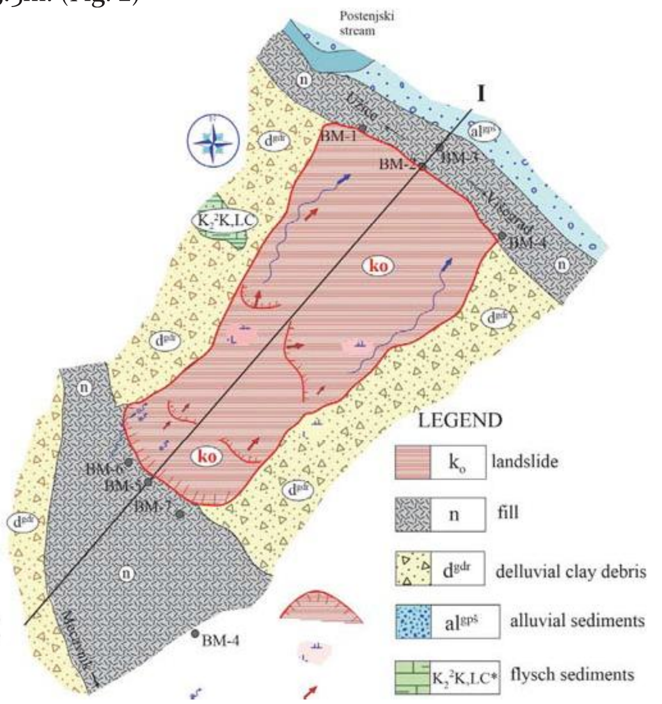

Fig. 2 Location plan of the landslide „Mokra Gora" on the road IB 28

For the characteristic geotechnical cross-section of terrain I – I (Fig. 3), the two-dimensional back stability analyses was done using Janbu's method. In this way the value of mobilized angle of internal friction $\varphi^{2D} = 29^o$ was obtained.

For three-dimensional stability analysis of landslide „Mokra Gora", using proposed approximate procedure, it is necessary to determine following :

- width of equivalent sliding body B_e
- disturbing forces in sliding body obtained by back stability analysis D
- lateral resisting forces R_{L1} and R_{L2}. These forces are proportional to lateral shear resistance and lateral areas of equivalent sliding body.

Then, the three-dimensional stability analysis (Eq. 2) was done with the angle of internal friction $\phi = 29^o$ and the safety factor $F_S^{3D} = 1.06$ was obtained. So the mobilized angle of internal friction for three-dimensional conditions is $\varphi^{3D} = 27.6^o$.

Comments on obtained results

The angle of internal friction is determined from the three-dimensional stability analysis of landslide „Mokra Gora". Such obtained value corresponds to the angle which is defined by laboratory tests in Highway Institute in Belgrade. The value of angle of internal friction, determined by three-dimensional stability analysis, should be used in designing remedial measures for landslide „Mokra Gora". In the connection with the results of stability analyses, it has to be pointed out that the differences in the safety factor obtained from 2D and 3D analyses are not high. However, when it is considered that for designing remedial measures of landslides in Serbian geotechnical practice, often is adopted that the satisfactory safety factor is $F_s = 1.15$-1.20, then this increase of F_s (from 1.0 to 1.06) and appropriate decrease of ϕ (from 29.0^o to 27.6^o), may be important in obtaining the rational engineering solution (Code, 1990).

An illustrative example about that is the old landslide in stiff clay at Sandnes, Norway (Hutchinson, 1988). The landslide has been activated by toe excavation. Before the excavation safety factor was only 1.02. The excavation brought this value down to 1.0. The initial remedial fill, which arrested the movements, increased safety factor to 1.03. This value was subsequently increased to 1.06 for permanent stabilization. From above it follows that for landslides are particularly important to avoid breaking down safety factors (by erosion, cutting etc.) and not to ensure their high values.

Conclusion

The conclusions of this paper are the following:

- stability analysis of landslide is in fact three-dimensional problem. In most cases the difference involved in applying 2D analysis to a 3D landslide is not high and is less than 10%, but in extreme cases it can go as high as 50%.
- when 3D effects of the landslide are significant then they should be involved in the stability analysis.
- application of the equivalent sliding body method on 3D stability analysis requires high quality at geotechnical investigation and good engineering judgment.

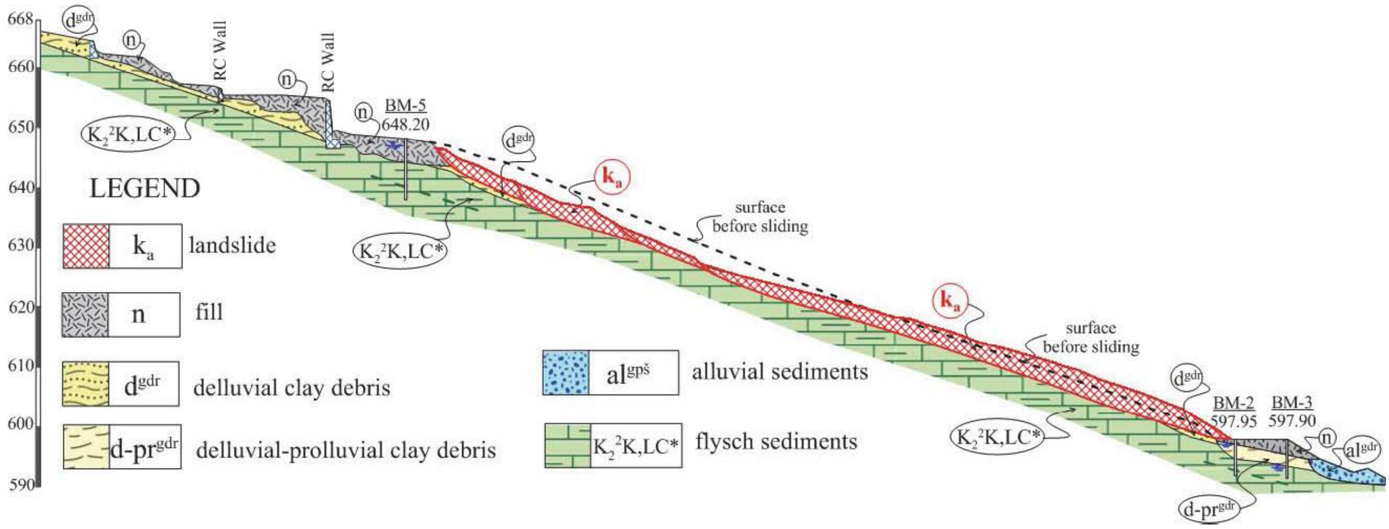

Fig. 3 Characteristic geotechnical cross-section of terrain I – I for landslide „Mokra Gora“

- if in the back stability analysis the 3D effects are neglected, then increased values of shear strength along the sliding surface are obtained regarding to the correct values and it leads, in design of remedial measures, to the solutions that are not on the side of safety.

These conclusions were confirmed in the example of the landslide „Mokra Gora“.

On the basis of above it can be concluded that 3D stability analyses are especially important in evaluating remedial measures for landslides that slip along the pre-existing sliding surfaces (Hutchinson, 1988). It is characteristic for numerous landslides in Serbia.

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