Value of partial factors for EC 7 slope stability analysis: solved "mystery"?

Jovan Papić
Chair of Geotechnics, Faculty of Civil Engineering, Skopje, R. Macedonia

Ljupčo Dimitrievski
Chair of Geotechnics, Faculty of Civil Engineering, Skopje, R. Macedonia

Verka Prolović
Chair of Civil Engineering Geotechnics, Faculty of Civil Engineering and Architecture, Niš, R. Serbia

KEYWORDS: Eurocode 7, partial factors, slopes, DA 3, global safety factor

ABSTRACT: Although the era of Eurocodes has started, some countries are still in the process of introducing them. This is specially related to the geotechnical EC 7 which is "designed" in a way to be easily accepted by different countries. According to it, each country has to choose adequate design approach for each geotechnical design and to select appropriate partial factors due to which application there are three different DAs. The ECs were expected to minimize the design differences between the countries, especially present in the field of geotechnics, and they principally fulfilled the task, but there have also remained further tasks e.g. to reduce the DAs and NDPs.
Beside foundations and retaining walls, slopes are one of the most common geotechnical structures. But, there are some opposite opinions about the selection of DA and partial factors. This paper tries to make an attempt to demystify them and to recommend a way for selection of partial factors. Namely, through mathematical relations, implementing Bishop's method for slope stability, it has been given support to DA 3 and it was shown that the values of partial factors, which are going to be included in the further National Annex, should be equal to the former global safety factor. This explanation can be useful for other countries interested in EC 7 which still haven't made their selection and can also help on the way of minimizing the number of design approaches.

1 INTRODUCTION

Slopes are structures that are often found in construction and mining, so it is clear why one of the priorities for selecting the appropriate design approach (DA) and partial factor (PF) in drafting the National Annex to Eurocode 7 is set on them. Until now, slopes have been designed and analyzed in accordance with proven methods based on the global factor of safety (FS). One of the most popular methods to calculate their limit equilibrium stability is certainly the Bishop's method, where the iterative calculation is carried out by the following equation:

$$Fs = \frac{\sum_{i=1}^{n}\left[c'\cdot b + (W - u\cdot b)\cdot \tan\phi'\right]\cdot m_{\alpha}}{\sum_{i=1}^{n} W\cdot \sin\alpha} \tag{1}$$

where

$$m_{\alpha} = \frac{1/\cos\alpha}{1 + \tan\alpha \cdot \tan\phi'/Fs} \quad (2)$$

Other methods usually vary in regards of treatment of inter-slice forces (Maksimović 2008), but calculations and analyses have shown that they do not affect the amount of the partial factors.

2 FEW ARGUMENTS ON THE SIDE OF SELECTED DESIGN APPROACH

For each geotechnical structure, the countries should select one/two/three of the offered DA which would be appropriate for their current practice and to make decision on the value of partial factors due to which application there is principle difference among the approaches (Frank et al. 2004). The presence of global factor in the equation for calculation of slope stability may mislead to adopt DA 2 as appropriate. But, besides the global factor, the denominator of the m_{α} member also includes the tangent of the angle of internal friction, which is to be divided exactly by the factor of safety, i.e.

$$\tan\phi' / Fs \quad (3)$$

This can be recognized as a reduction of the specified shearing resistance parameter (SRP). As it is already known, such reduction is performed in DA 1 C 2 and DA 3; but having in mind that DA 1 demands two calculations, the suitable DA applicable to a current practice not only in the Balkan region, but even wider, should be located in DA 3. From this point of view, it offers some more important advantages, when compared to others.

Namely, since the soil's shearing resistance in a plane depends on the normal load acting on that plane, its strength is a function of load, and thus requires attention when setting the partial factors, because the increase of the load with PF leads to increase in the strength. All of the loads are increased in the DA 1 C 1, as well in the DA 2. This is only one reason why during the selection of the appropriate approach for analyzing slope stability it is advisable to adopt DA 3: there the constant loadings due to weight of soil do not increase, what is also important in performing stress-strain calculation in the finite elements method (FEM) software, while multiplying only the variable loads. Moreover, when analyzing the stability using the DA 3, all loads - either structural or geotechnical - are treated as if originating from the ground, and thus are not subject to change of values, because the partial factor is 1.0.

Performing calculations with characteristic values might seem as encouraging DA 2* as a probable to use in slope stability analysis. Still, this advantage is not applicable in case of slope stability simply because it is difficult to determine where the resistance subjected to reduction appears in slopes. Besides that, a part of the soil has a favourable effect on stability, while its upper part causes a disturbance, thus the Single Source Principle in the application of DA 2 for slope stability analysis does not apply.

For these obvious reasons, many countries that implement Eurocode 7, i.e. the vast majority of those who do not accept double calculation in DA 1, have recommended the approach 3 for slope stability analysis (only one or two countries prefer DA 2 (Bond 2011), even though in an unprincipled manner). Conceptually, almost identical is the DA 1 C 2, which is also the most competent in DA 1 since milder slopes are obtained, and it allows c'/φ' reduction: this is an option to determine the safety factor for software based on FEM. This insight is encouraging for the future in terms of harmonization when the DA 3, most certainly, will be recommended for calculation of slope stability according to Eurocode 7 (Schuppener 2010). This approach will in R. Macedonia also be recommended for a numerical modelling by FEM for slopes and it will serve for a case in which slopes and foundations are simultaneously treated since DA 3 is also recommended for designing spread foundations (Papić et al. 2011). Thus, their consistency is enabled, respecting that ground and structure are parts of the same problem, in direct contact and interaction (Simpson 2008).

3 DETERMINATION OF VALUE OF PARTIAL FACTORS

Following this specific terms and conditions regarding the selection of a design approach, it should be continued with determination of PF to reduce the SRPs of the soil. The basic and main condition which is to be fulfilled for determination of the PF for the SRPs is to provide the same extent of stability so far prescribed, i.e., to achieve the same slope inclination.

If $c = 0\ kPa$ and $u = 0\ kPa$, then the Bishop's expression (1) can be reduced to

$$Fs = \frac{W \cdot \tan\phi' \cdot m_\alpha}{W \cdot \sin\alpha} \tag{4}$$

and introducing (2) in (4), will get

$$Fs = \frac{\tan\phi'}{\sin\alpha \cdot \cos\alpha + \sin^2\alpha \cdot \tan\phi' / Fs} \tag{5}$$

From this expression can be derived that

$$\tan\phi' = Fs \cdot \sin\alpha \cdot \cos\alpha + \sin^2\alpha \cdot \tan\phi' \tag{6}$$

$$\tan\phi' \cdot \left(1 - \sin^2\alpha\right) = Fs \cdot \sin\alpha \cdot \cos\alpha \tag{7}$$

$$\tan\phi' = Fs \cdot \tan\alpha \tag{8}$$

where the allowable safety factor is not constant, but is a function of the load case in which the stability is considered.

If (5) is applied in terms of ultimate limit state, with FS = 1.0, then the design value of the angle of friction should be entered instead of *tan* ϕ':

$$\tan\phi_d = \frac{\tan\phi'}{\gamma_\varphi} \tag{9}$$

so the expression (5) would be as follows

$$Fs = \frac{\tan\phi_d}{\sin\alpha \cdot \cos\alpha + \sin^2\alpha \cdot \tan\phi_d / Fs} \tag{10}$$

with further derivation

$$\tan\phi_d = \sin\alpha \cdot \cos\alpha + \sin^2\alpha \cdot \tan\phi_d \tag{11}$$

and, similar to the fore mentioned transposing of *tan* ϕ_d' to the left side and adjusting the trigonometric expression

$$\tan\phi_d = \tan\alpha \tag{12}$$

i.e. with respecting (9)

$$\tan\phi' = \gamma_\phi \cdot \tan\alpha \tag{13}$$

Equalizing the expressions (8) and (13) with the same member *tan* ϕ' on the left side, would gain

$$Fs \cdot \tan\alpha = \gamma_\phi \cdot \tan\alpha \tag{14}$$

and finally

$$\gamma_\phi = Fs\,. \tag{15}$$

According to this derivation and additional indications, it can be stated that the PF used to reduce the angle of friction (i.e. its tangent in ultimate limit state conditions) while maintaining the same level of security that was previously provided with a global factor of safety, does not depend on geometrical, material, or loading properties, but only on load case in which the stability of the treated slope is considered: permanent, transient or incidental state, etc!

Similar approach can also determine the PF for cohesion, considering the soil with friction and cohesion and with no pore pressure, so in the case of global factor:

$$Fs = \frac{\left(c' \cdot b + W \cdot \tan\phi'\right) \cdot m_\alpha}{W \cdot \sin\alpha} \tag{16}$$

$$Fs = \frac{\tan\phi' \cdot m_\alpha}{\sin\alpha} + \frac{c' \cdot b \cdot m_\alpha}{W \cdot \sin\alpha} \tag{17}$$

Arranging the equation by *c'* gains

$$c' = \left(\frac{Fs}{m_\alpha} - \frac{\tan\phi'}{\sin\alpha}\right) \cdot \frac{W \cdot \sin\alpha}{b} \tag{18}$$

Expression (18) may be used in limit state condition (FS=1.0) when PF are included, with

$$c_d = \frac{c'}{\gamma_c}, \tag{19}$$

so

$$c_d = \left(\frac{Fs}{m_{\alpha,d}} - \frac{\tan\phi_d}{\sin\alpha}\right) \cdot \frac{W \cdot \sin\alpha}{b} \tag{20}$$

where from

$$c' = \gamma_c \cdot \left(\frac{1.0}{m_{\alpha,d}} - \frac{\tan\phi_d}{\sin\alpha}\right) \cdot \frac{W \cdot \sin\alpha}{b} \tag{21}$$

Similarly as previously, equating the expressions (18) and (21) with *c'* on the left side implies that

$$\gamma_c \cdot \left(\frac{1.0}{m_{\alpha,d}} - \frac{\tan\phi_d}{\sin\alpha}\right) \cdot \frac{W \cdot \sin\alpha}{b} = \left(\frac{Fs}{m_\alpha} - \frac{\tan\phi'}{\sin\alpha}\right) \cdot \frac{W \cdot \sin\alpha}{b} \tag{22}$$

and, considering $\gamma_\phi = Fs$,

$$\gamma_c = \frac{Fs \cdot \dfrac{1 + \dfrac{\tan\alpha \cdot \tan\phi'}{Fs}}{\dfrac{1}{\cos\alpha}} - \dfrac{\tan\phi'}{\sin\alpha}}{\dfrac{1 + \dfrac{\tan\alpha \cdot \dfrac{\tan\phi'}{Fs}}{1.0}}{\dfrac{1}{\cos\alpha}} - \dfrac{\dfrac{\tan\phi'}{Fs}}{\sin\alpha}} \tag{23}$$

$$\gamma_c = \frac{Fs \cdot \left(\frac{1+\frac{\tan\alpha \cdot \tan\phi'}{Fs}}{\frac{1}{\cos\alpha}} - \frac{\tan\phi'}{Fs \cdot \sin\alpha} \right)}{\frac{1+\frac{\tan\alpha \cdot \tan\phi'}{Fs}}{\frac{1}{\cos\alpha}} - \frac{\tan\phi'}{Fs \cdot \sin\alpha}} \tag{24}$$

which already demonstrated, implies that

$$\gamma_c = Fs\ ! \tag{25}$$

The same would be concluded even if soil with no friction was treated. Thus, it is confirmed that in the calculation of slope stability the amount of PF by which are reduced SRPs is equal both for the tangent of the angle of friction and cohesion, and is equal to the former global factor of safety. Beside, adopting the same value of PF for both SRPs has advantage for obtaining safety factor in FEM analysis since it opens possibility of implementation of c'/φ' reduction during which both SRPs are equally decreased.

However, the intensity of the global safety factor depends on the conditions in which the stability of slopes is considered: permanent, transient, or incidental, sudden discharge, back analysis etc, which may also vary depending on the structure (dam, road, open mine, etc.). EC 7 and its Annexes did not offer such classification of PF values, since they are proposed as constant (Eurocode 7 2004) and independent of the case considered, which is one of its shortcomings. However, EC 0 and EC 1 open the possibility of varying PF, depending on the consequences classes, classes of reliability, and load case: permanent or transient, that exactly suits former Yugoslavian and now Macedonian, Serbian etc. current practice! Pat of the above mentioned is stated in particular Annexes: UK, Germany, Austria, Sweden, Finland and so on (Orr 2011). At the same time, the proposed values maintain the existing safety level, i.e. same slope inclination, which is also important during any repairs or upgrades; it avoids future threats to serviceability of slope and allows engineers to easier adjust to new calculations in accordance with the EC7.

The presented procedure enables analysis to be used not only in the application of the Mohr–Coulomb law, but also in nonlinear failure envelope of hyperbolic type (Maksimović 2008) where the angle is not constant, i.e. is related to stresses. Its realistic description of the shear resistance in wide stress domain is of great help in optimization of slopes, because of rational usage of soil shear resistance, especially in the zone of lower stresses which often is the critical case for designing slopes. Namely, we may recall that the design SRP is the characteristic one divided by PF:

$$\tau_d = \sigma' \cdot \frac{\tan\phi'}{\gamma_\phi} \tag{26}$$

in which case $\gamma_\phi = FS$ thus obtaining the already known equation

$$\tau_d = \frac{\tau}{FS} \tag{27}$$

then the latter equation can be directly used to describe the nonlinear failure envelope, for example through "user-defined model" option, when it is sufficient to "correct" laboratory obtained values for the shearing stress by division with FS, i.e. γ_ϕ, and reduced that way to enter them into the software. This way, the slope that previously has had a global safety factor of 1.40, in the limit state, i.e. after the division of shearing stress by 1.40, will have a factor of 1.00. In both cases the specified values of factor shall refer to the same sliding surface.

4 CONCLUSIONS

In the analysis of slope stability, one might conclude that Design Approach 3 fits the demands for keeping the existing safety degree and slope inclination as well it offers other opportunities as described above, among which is also the easier application of FEM analyses and transfer of engineer's practical work from global to partial safety factors. Because of these reasons, it was adopted in various European countries and is expected to be adopted in others looking forward to introducing Eurocodes. Thus the number of design approaches, at least for slope stability analysis, could be reduced in further EC 7 revisions.

Through presented relations, it was shown that the partial factors for shearing resistance parameters are not constant, but their value is equal to the former global safety factor which depends strictly upon load case: permanent, transient, incidental etc. This procedure and same factors' value are also favourable from the aspect of enabling the analysis of slope stability in the description of shearing resistance with nonlinear failure envelope, as well as when applying FEM where c'/φ' reduction is used to determine the safety factor. All of these findings were confirmed by numerical analyses which are not presented in this paper (Papić et al. 2012).

But, since that these load case values are different among the countries, to enable elimination of possible appearance of many partial factors, it is probable to suggest increasing the number of laboratory tests through which SRPs are determined and such to decrease the value of partial factors without reduction of their confidence or endangering safety.

REFERENCES

Bond, A. (2011). Past, present and future of Eurocode 7. 3rd ISSMGE Webinar, 2011
Eurocode 7. (2004). Geotechnical design - Part 1: General rules.
Frank, R., Bauduin, C., Driscoll, R., Kavvadas, M., Krebs Ovesen, N., Orr, T., Schuppener, B. (2004). Designer's guide to EN 1997-1. Thomas Telford, London, 216p
Maksimović, M. (2008). Soil mechanics. 4th Edition, AGM knjiga, Belgrade, 643p
Orr, T. (2011). Experiences with the Implementation of Eurocode 7 in Europe. Workshop: Safety Concepts and Calibration of Partial Factors in European and North American Codes of Practice, Delft
Papić, J.Br., Dimitrievski, Lj., Prolović, V. (2011). Is anybody (else) afraid of Eurocode 7?. 4th scientific and practical meeting "Geotechnical aspects of civil engineering", Zlatibor, R. Serbia, pp.9-16
Papić, J.Br., Dimitrievski, Lj., Prolović, V. (2012). Verification of selected design approach and partial factors for slope stability analysis according to EC 7. 2nd International scientific meeting GTZ 2012 "State and trends of civil engineering", Tuzla, Bosnia and Herzegovina (accepted paper)
Schuppener, B. (2010). Update on Eurocode 7, its implementation and maintenance, 2nd International Workshop on Evaluation of Eurocode 7, Pavia
Simpson, B. (2008). Approaches to ULS design – The merits of Design Approach 1 in Eurocode 7. International seminar on Eurocode 7 and geotechnical aspects of Eurocode 8, Struga, R. Macedonia, pp.125-136