Design software comparison of reinforced steep slopes

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ABSTRACT: Three design programs have been used for comparison purposes on standardized examples of reinforced steep slopes. The study shows that - beside geotechnical and geosynthetic input values and corresponding safety factors - there is an influence on the result because of the used design software and the applied analytical model, which should be considered in security aspects and project requirements. The observed variations in result should help for the evaluation of a design program. It is given the possibility to benchmark other software tools outside this study – after having calculated the same examples here presented. As a consequence, a model safety factor will be introduced in order to make comparable the results received from different calculation models.

1 INTRODUCTION

The design concept with the partial safety factors enables to determine the role of the calculation model. Several design programs are available on the market with more or less differences. It is up to the user to decide, which software to use for the - to him most advantageous - stability verification.

The following questions can be made in the context of design:

- How (safe) should we design?
- Which security is necessary for a lifetime of 100 years?
- What possibilities do offer the partial safety factor concept?
- Can we take into account the differences between design models? If yes, how?

Until today there still exist different opinions and procedures of engineers, how to design a reinforced steep slope. A Swiss design approach is presented in this paper straightforwardly.

2 SCOPE OF THE STUDY

The present study should contribute to develop a common sense in design between the engineers of different companies and countries. In order to define the role of the calculation model, twelve fictitious cases were calculated with 3 different software tools. For evaluation reasons, it is possible to calculate the same cases also with other design tools not examined in this study. So, the present work is extendable for other calculation programs. It is important for job owners and engineers to know the differences in order to judge the security level, for example, if there are presented different results of different programs on the same object.

The design concept with the partial safety factors should be used in order to define the uncertainties and the design requirements under respect of the corresponding Standards in force.

3 BASIS

The Swiss Standards SIA 260, SIA 261, SIA 267 and SN 670 242 prescribe the partial design concept in accordance with the Eurocode EC7.

The main point of design is the loss of the static equilibrium, so-called ultimate limit state ULS. Outgoing from the ULS, different partial factors are applied on load (load factors), on the resistance of soil (safety factor SF on tan ϕ', SF on coesion c') and on the strength of geosynthetic (A_1-A_5, γ_R). The idea is, that one can vary and dose the safety factors in function of the project requirements.

The design strength of a geosynthetic can be calculated, as follows:

$$z_{Rd} = \frac{z_R}{\gamma_R} = \frac{r_{min}}{A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5 \cdot \gamma_R} \geq z_d \; [\mathrm{kNm^{-1}}] \qquad (1)$$

z_{Rd} = long term design strength [$\mathrm{kNm^{-1}}$]
z_R = effective long term strength [$\mathrm{kNm^{-1}}$]
γ_R = 1.40 partial safety factor on geosynthetic strength after SN 670 242. Independent from product type.
z_d = acting force to design [$\mathrm{kNm^{-1}}$]
r_{min} = minimal value of short term strength, average value minus 95% confidence limit [$\mathrm{kNm^{-1}}$]
A_1 = reduction factor for creep resp. deformation behaviour under constant loading after EN ISO 13431 [-]
A_2 = reduction factor for damages due to transportation, installation and compaction after ENV ISO 10722-1 [-]
A_3 = reduction factor for joints and connections after EN ISO 10321, if it is forseen [-]
A_4 = reduction factor for environmental effects (UV-stability, resistance against chemicals, micro-organism, and animals) / durability after EN 12224 [-]
A_5 = reduction factor for dynamic effects in railway constructions [-]

For each analysis of the failure mechanism, the following verification is to conduct:

$$E_d \leq \frac{R_d}{\gamma_m} \qquad (2)$$

E_d = design value of stress
R_d = design value of resistance
γ_m = model safety factor
Differences of the calculation method can be considered with this factor, which is often treated in the partial design concept as 1.00.

4 ANALYTICAL METHODS

The following design software have been used in the comparison:

- ReSlope 4.0
- ReSSA Reinforced Slope Stability Analysis 3.0
- DC-Geotex 3.3

ReSlope 4.0 does design: with given geometry, simple geology and defined geosynthetic and safety factors, as result, the anchorage length and the needed geosynthetic density is calculated. Logarithmical spirals, as failure curves are used with the Bishop-method.

ReSSA Reinforced Slope Stability Analysis 3.0 analyses a predefined situation with the geosynthetic disposition. Bishop's circle and the sliding (2-part-wedge with a horizontal slip joint) after Spencer, where the lateral forces between the slices are considered, are offered as possible calculation methods. The result of each calculation is the lowest found factor of safety. If the result is an insufficient safety factor, we have to change the geosynthetic disposition and reanalyse the situation.

DC-Geotex 3.3 does analysis, similar to ReSSA. The internal stability is calculated by 2-part-blocs (no slices), whereas the earth pressure is worked out of a numerical method of Culmann and the safety factor is defined after Fellenius. For the global stability the rupture circle is divided into slices and calculated after the Krey-Bishop-method.

5 CASE-STUDY EXAMPLES

Six different cases in two situations have been calculated by the authors in collaboration with two students of the Engineer School Fribourg in Switzerland (*figure 1*).

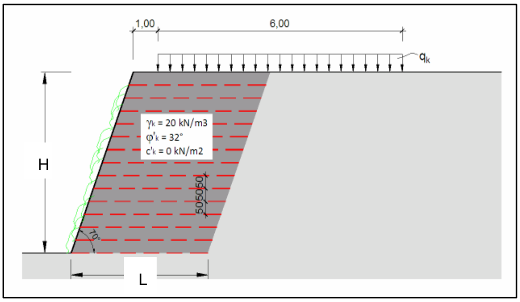

Figure 1. General illustration of the case-study example

Table 1. Soil parameters and safety factors (after SIA 267)

	Characteristic values	Partial safety factors	Design values
Specific weight	$\gamma_k = 20$ kN/m^3	SF_γ = 1.00	$\gamma_d = 20$ kN/m^3
Int. friction angle	$\phi'_k = 32.0$ °	$SF_{\tan\phi'}$ = 1.20	$\phi'_d = 27.5$ °
Apparent cohesion	c'_k = 0 kPa	$SF_{c'}$ = 1.50	c'_d = 0 kPa

The soil parameters were taken for the fill soil and the existing soil as a homogenous geology. The soil input values are shown in *table 1*.

Neglecting the cohesion part, the design friction coefficient between geosynthetic and soil is to calculate in accordance with SN 670 242 :

$$\tan \delta'_d = \frac{a_{\phi'} * \tan \phi'_d}{\gamma_R} \qquad (3)$$

$\tan\delta'_d$ = design friction coefficient [-]

$a_{\phi'}$ = product-/soil-dependent friction rapport [-],

$\tan\phi'_d$ = design coefficient of the internal friction angle of soil [-]

γ_R = 1.20 partial safety factor on friction product/soil after SN 670 242. Independent from product type.

Thus, for a granular soil in question, the applied geogrids has the following values:

$$\tan\delta'_d = \frac{a_{\phi'} * \tan\phi'_d}{\gamma_R} = \frac{0.90 * \tan\phi'_d}{1.20} = 0.75 * \tan\phi'_d \quad (3a)$$

As reinforcement, extruded geogrids in HDPE were used in the calculation with the characteristics below (*Table 2*).

Table 2. Strengths of the applied geosynthetics

Geosynthetic	r_{min} [kN/m']	z_{Rd} [kN/m']
GGR 1	45.0	14.2
GGR 2	60.0	18.9
GGR 3	90.0	28.3

The vertical spacing of the geogrid was taken to 0.50 m as a constant value. In a first stage, also the geogrid length, with L = 0,80 * H was taken as constant.

Table 3. Input data of the cases 1 - 6

	Slope angle [°]	Height H [m]	Ancorage L [m]	Load q_k [kPa]	Geosynthtic type
Case 1	70°	4.0	3.2	0	GGR 1
Case 2	70°	4.0	3.2	30	GGR 1
Case 3	70°	7.0	5.6	0	GGR 2
Case 4	70°	7.0	5.6	30	GGR 2
Case 5	70°	10.0	8.0	0	GGR 3
Case 6	70°	10.0	8.0	30	GGR 3

Table 3 shows for the first six cases (cases 1 to 6) the input data of dimensions, loads and applied geosynthetics.

In a second stage, i.e. for the cases 1' to 6', - with the same height, same geogrid and the same vertical spacing of the geogrid layers - the optimized anchorage length was searched for.

6 RESULTS

6.1 Analysis

The results of analysis with a constant anchorage length are shown in the *tables 4 and 5*. The differences between the results appear to be small at first, although, there is a visible tendency, that DC-Geotex delivers up to 4% higher safety factors, than the sliding-model of ReSSA (*table 6*).

Table 4. Results of ReSSA (analysis)

	H [m]	L [m]	**SF_{Bishop}**	**$SF_{Sliding}$**	*Critical failure*
Case 1	*4.0*	3.20	**1.34**	**1.27**	sliding
Case 2	*4.0*	3.20	**1.05**	**1.04**	sliding
Case 3	*7.0*	5.60	**1.31**	**1.23**	sliding
Case 4	*7.0*	5.60	**1.11**	**1.07**	sliding
Case 5	*10.0*	8.00	**1.32**	**1.26**	sliding
Case 6	*10.0*	8.00	**1.23**	**1.17**	sliding

Table 5. Results of DC-Geotex (analysis)

	H [m]	L [m]	**SF_{Bishop}**	*Critical failure*
Case 1	*4.0*	3.20	**1.32**	Bishop
Case 2	*4.0*	3.20	**1.08**	Bishop
Case 3	*7.0*	5.60	**1.27**	Bishop
Case 4	*7.0*	5.60	**1.11**	Bishop
Case 5	*10.0*	8.00	**1.28**	Bishop
Case 6	*10.0*	8.00	**1.22**	Bishop

Table 6. Comparison of safety factors10. + value: DC-Geotex shows a higher SF, - value: DC-Geotex shows a lower SF

	Diff. SF btw. DC-Gtx & ReSSA Bishop [%]	Diff. SF btw. DC-Gtx & ReSSA Sliding [%]
Case 1	-1.5	3.8
Case 2	2.8	3.7
Case 3	-3.1	3.1
Case 4	0.0	3.6
Case 5	-3.1	1.6
Case 6	-0.8	4.1
Avarage Ø	Ø -1.0	Ø 3.3

The same difference can be discovered between the Bishop's and the Spencer's safety factors within the ReSSA program.

6.2 Design

The results of the six examples are shown in the *tables 7 to 9* with the objective to optimize the anchorage lengths.

Table 7. Results of ReSlope (design)

	H [m]	SF_{Bishop}	$SF_{Sliding}$	**L [m]**	*Critical failure*
Case 1'	*4.0*	1.10	1.00	**2.08**	sliding
Case 2'	*4.0*	1.09	1.00	**3.19**	sliding
Case 3'	*7.0*	1.10	1.00	**3.63**	sliding
Case 4'	*7.0*	1.10	1.00	**4.74**	sliding
Case 5'	*10.0*	1.10	1.00	**5.19**	sliding
Case 6'	*10.0*	1.08	1.00	**5.99**	sliding

Table 8. Results of ReSSA (design)

	H [m]	SF_{Bishop}	$SF_{Sliding}$	**L [m]**	*Critical failure*
Case 1'	*4.0*	1.05	1.00	**1.87**	sliding
Case 2'	*4.0*	1.00	1.00	**2.87**	sliding
Case 3'	*7.0*	1.02	1.00	**3.25**	sliding
Case 4'	*7.0*	1.02	1.00	**4.65**	sliding
Case 5'	*10.0*	1.02	1.00	**4.60**	sliding
Case 6'	*10.0*	0.99	1.00	**5.60**	sliding

Table 9. Results of DC-Geotex (design)

	H [m]	SF_{Bishop}	L [m]	*Critical failure*
Case 1'	*4.0*	1.00	**1.80**	Bishop
Case 2'	*4.0*	1.00	**2.75**	Bishop
Case 3'	*7.0*	1.01	**3.35**	internal stability
Case 4'	*7.0*	1.00	**4.60**	Bishop
Case 5'	*10.0*	1.01	**4.80**	internal stability
Case 6'	*10.0*	1.03	**6.00**	internal stability

The anchorage length of the geosynthetic layers has been calculated about 10% longer by ReSlope than by the other two programs. However, between the results of ReSSA and DC-Geotex, there has been observed no tendentious difference: the variation is about +/- 5%.

7 DISCUSSION

Hufenus R. et al. 2009 showed in their VSS-research project, that different design methods led to variations of up to 100% in the design force of the geosynthetic layers (*figure 2*).

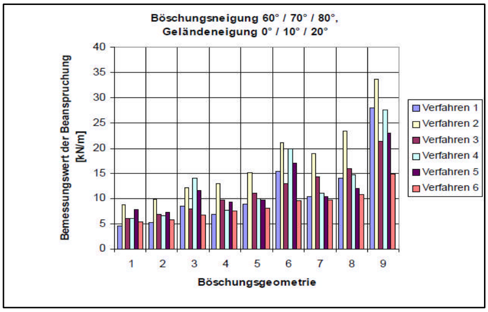

Figure 2. Geosynthetic design forces (after Hufenus et al. 2009)

Although the obtained results of the current study in safety factors and anchorage lengths show smaller variations, than the presented ones in geotextile stresses of *figure 2*, the obtained results motivate the authors to introduce a partial factor for the design method, so-called model safety factor γ_m.

The model safety factors listed below can be used in the formula *(2)* to distinguish between the design methods:

- Krey-Bishop's circle $\gamma_m \geq 1.05$ (ev. 1.10)
- Spencer's sliding $\gamma_m \geq 1.00$

The optimization of the geosynthetic spacing and the use of different geogrid resistance on the same object were not examined, because the study had no objective to come to a cost-effective and ready-for-execution solution in the internal stability design, but to evaluate design models.

The present straightforward examples are invented and assumed to be installed on a horizontal surface. In reality, steep slopes are often built on inclined surfaces, so global failure will become more accentuated.

8 CONCLUSION

A model safety factor can be used to consider variations of result coming from different methods or software.

Definitely, it is important to know, how to use a program, because the right use of software might have a much bigger influence on the result, than the here noticed variations. If the project engineer has any doubts, it is still recommended to contact a specialized office or company for design-questions.

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