Stability design of a geosynthetic reinforced rock cuttings wall

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Abstract. Rocks excavation with tunnel boring machines induces a lot of cuttings. This granular material needs to be stored. When reinforced by geosynthetics, significant tensile stresses can be obtained in the resulting composite structure which allows to build steep slopes. A real case study of a reinforced rock cuttings wall is presented in this paper. To study accurately this complex problem, two calculation methods were used: a limit equilibrium (using the Bishop criteria), classically used for these kinds of stability problems and two-dimensional finite element calculations. These two methods are different and give different results. The FE calculation is the more representative and the more conservative method for such designs when considering the studied case.

1 Introduction

Geosynthetic reinforced earth retaining walls constructed with geosynthetic straps, geogrids or geotextiles are now a mature technology of composite structures. This technique, introduced in the 1970s [1], showed its performance during strong earthquakes [2, 3].

Reinforced earth retaining walls are cost effective retaining structures, capable of supporting much larger deformations than traditional retaining walls. The design of such structures is often done by a limit equilibrium or limit analysis methods. The use of numerical methods to design such embankments is less used. In the present article, based on a real case-study, two methods are used (limit equilibrium and numerical methods) to evaluate the stability of a rock-cuttings reinforced wall. Their results are compared in terms of safety factors.

2 Theoretical aspects

The Bishop formulation consists in the evaluation of a limit equilibrium between the destabilizing and stabilizing forces. This implies the definition of a kinematic failure, involving a moving block slipping along the slope. All along the slipping surface, stabilizing forces due to the granular material shear resistance appear, countering the moving block weight. Reinforcements also bring stabilizing forces, retaining the moving block. The studied

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surfaces should be regular to get a solvable mathematical formulation of all the forces involved: the Bishop formulation is based on the optimization of circular surfaces. A safety factor is thus calculated as the ratio between stabilizing forces and destabilizing forces. If this factor is greater than 1, then the studied geometric configuration is stable and will not collapse.

In this paper, a two-dimensional finite element numerical model using a plane-strain calculation is also considered. This method is more complex than the Bishop one, but it allows obtaining results in all the model nodes discretization through an explicit formulation. The failure geometry does not need to be constrained and predefined as a circular one. The numerical model will naturally evolve in terms of stresses till the slipping surface begin to appear. Using the shear strength reduction method, it is possible to evaluate a safety factor. Slipping surfaces are visible through the deviatoric strain field. Higher values appear on the failure line.

3 Case-study: reinforced rock cuttings wall

The hydro-electric plant of Hône (Italy, Aosta Valley) is being renovated and a new derivation channel must be built, mostly underground, generating a lot of rock cuttings. A vegetated deposit will be created on the mountain slope near the underground channel entrance. The rock slope is naturally steep, a stability study is thus required to ensure the deposit stability. At its base, a reinforced rock-cuttings wall is added so that the deposit volume can be higher. This wall, constituted of three parts is separated by a construction track and will have a 60° inclination from the horizontal. Previous studies have considered the geotechnical data given in Table 1. In this study, the geotechnical parameters of the altered gneiss and rock cuttings were adjusted through a back analysis, considering that intact gneiss is not involved in the failure mechanism. Three level of geogrids are set to reinforce the cuttings wall, with a 1 meter vertical spacing. Their properties are given in the Table 2**.**

Table 1. Geotechnical initial dataset.

Material	γ [kN/m^3]	Criterion	c' [kPa]	ϕ' [°]	$\sigma_{c,i}$ [MPa]	D	m_b	s	a
Altered gneiss	20	Mohr-Coulomb	0	35	-	-	-	-	-
Rock cuttings	20	Mohr-Coulomb	0	35	-	-	-	-	-
Healthy gneiss	27	Hoek-Brown	-	-	141	0	5.991	0.0117	0.503

Table 2. Geogrids mechanical properties.

Parameter	Value	Unit
Tensile strength	50.0	kN/m
Maximum friction	40.0	kPa

A pseudo-static calculation is done according to the Italian standards NTC2008 and NTC18. Considered coefficients are (given g=9,81 m/s²):

- Horizontally: k_h = 0.035112 g
- Vertically: k_v = ±0.017556 g

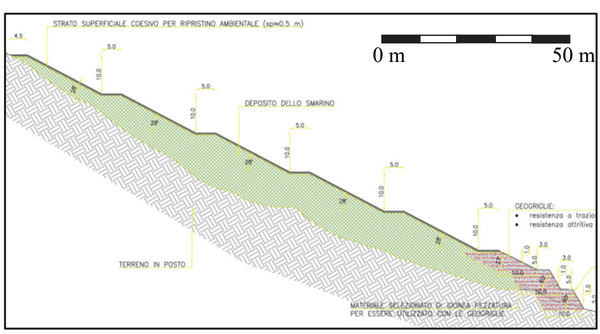

Figure 1. Rock cuttings projected deposit.

4 Case-study: Back-analysis of the actual situation

The actual situation does not show any sign of instability, which corresponds to a safety factor (S. F.) at least equal to 1.3 (when no partial coefficient is considered). Iterating on the cohesion and friction angle values for the altered gneiss, this section aims at finding their lowest value leading to a safety factor equal to 1.3. The Bishop analysis shows a critical surface on the upper slope part, as shown in Table 3. The Finite Element analysis confirms that the upper part is the most critical. Its results are given in Table 3. Both approaches show a critical slipping surface in the upper part, which is the steepest zone of the site. However, the numerical approach shows a surface slightly more complex than the circular one imposed in the Bishop's approach. The finite element approach appears to be more conservative, giving higher shear strength parameters to ensure the slope stability.

Table 3. Back-analysis results for altered gneiss.

Approach	**c'** [kPa]	**ϕ'** [°]	S. F. Upper zone	S. F. Medium zone	S. F. Lower zone
Bishop	4	37	1.3	1.5	1.6
Finite Element	10	40	1.3 (upper zone)		

5 Case study: Design of the rock cuttings storage

Calculations were made with the following 11-steps phasing:

- 0: Initial phase: initial situation using the parameters found in the back-analysis,
- 1 to 4: Realization of the reinforced rock cutting wall,
- 5 to 9: Realization of the 5 levels of unreinforced rock-cuttings deposit,
- 10: Pseudo-static calculations made for the seismic case, based on the final static phase.

According to the European and Italian standards (Eurocode 7 EN1997 and NTC18), some coefficients must be applied to the parameters and calculation results. These coefficients correspond to the Eurocode approach 1 – combination 2 (A2+M2+R2) described in these standards. The targeted safety factors are thus equal to 1.1 in static conditions and 1.2 in pseudo static conditions.

With both approaches, it appeared that the predefined geogrids length was too short, and that it was necessary increasing it to push away the slipping surface inside the soil mass. Table 4 shows the obtained results in terms of mixed / external and internal stability (Safety Factor and Work Ratio of the geogrids) for both approaches. For phases 5 to 10, two families of instabilities were studied: within the reinforced wall, and within the upper deposit.

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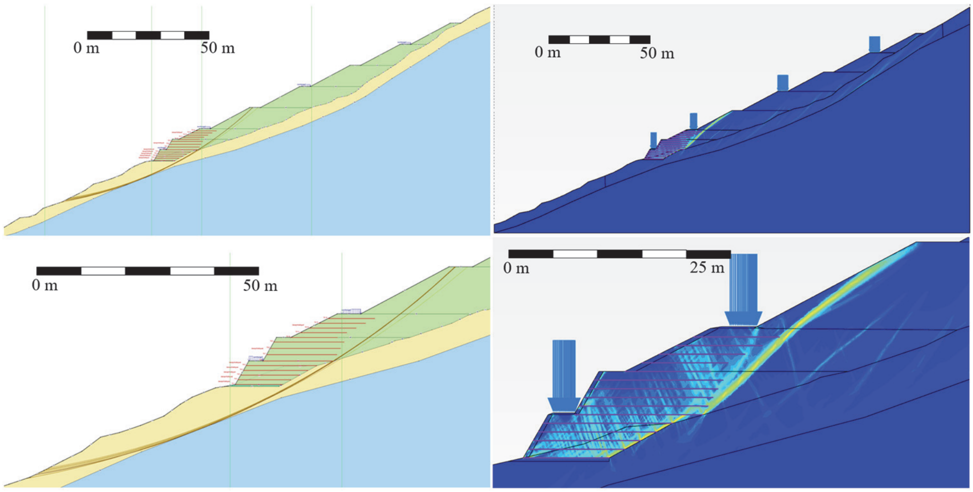

Figure **2** shows the obtained geometry of failure with both approaches at the final static phase (n°9).

Table 4. Stability analysis results

Phase	Bishop		Finite Element	
	Safety Factor	Work Ratio	Safety Factor	Work Ratio
1st level wall	1.8	0 %	1.1	9 %
2nd level wall	1.5	100 %	1.1	25 %
3rd level wall	1.3	87 %	1.1	25 %
1st level deposit	1.3	47 %	1.1	25 %
2nd level deposit	1.3	47 %	1.2	25 %
3rd level deposit	1.3	47 %	1.2	25 %
4th level deposit	1.3	47 %	1.2	25 %
5th level deposit	1.3	47 %	1.2	25 %
Earthquake	1.5	15 %	1.2	22 %

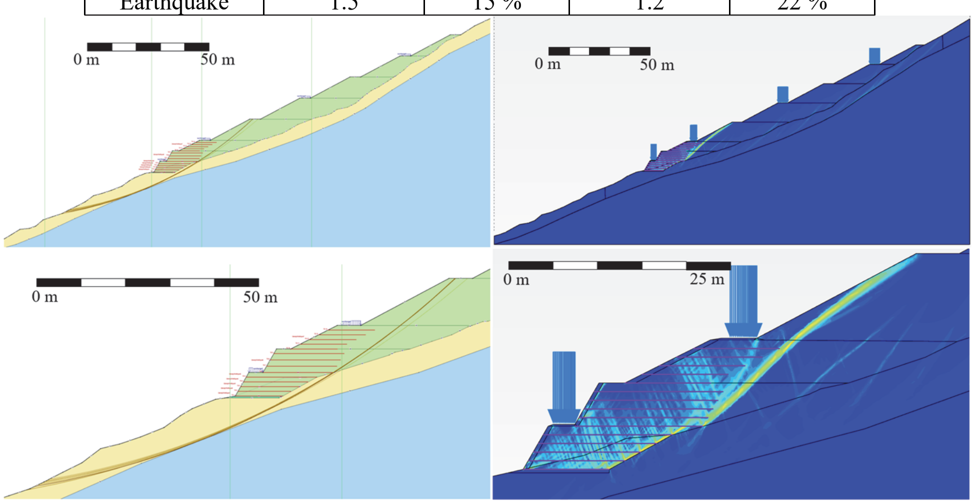

Figure 2. Geometry of failure (left: Bishop's critical slipping surfaces / right: deviatoric strain in finite elements model / up : whole model / down: zoom on the failure of the reinforced rock cuttings wall)

6 Conclusion and recommendations

It is shown in this comparative analysis that the Bishop approach is simpler to use, more direct, but cannot be representative of a more complex failure mechanism than a circular one.

The finite element approach is more complex but allows to investigate more complex failure geometries, which appear clearly different than a circular one. The finite elements approach appears much more conservative than the Bishop one regarding the external/mixed stability, as it allows a better failure mechanism evaluation. However, the Bishop approach seems more conservative regarding the working ratio of geogrids. The finite element approach also allows to check the soil mass deformations, its resulting work ratios might be more accurate. Only a comparison with an instrumented site will allow to define what method is the more accurate one.

Authors recommend using a finite element simulation when analysing the slope stability, especially for the detailed project phases, and/or for specific projects with a complex geometry and reinforcements. The interaction between reinforcements and surrounding ground appears complex, which implies a real need for a complete simulation tool.

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