Reinforcement design using geosynthetics for foundations with probability of dolinamento: Analytical calculation and numerical stress-strain model

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ABSTRACT

Karst zones are defined by their high solubility, porosity and consequence of subsidence occurrences. Considering that about 20% of of ice-free land is made up of karst regions, the present work aimed to reinforce by geosynthetics a hypothetical foundation subject to windings through the analytical methodology of Briançon and Villard (2007) and by modeling numerical stress-strain in RS2 software (Rocscience). Initially, a hypothetical foundation to be strengthened was defined, in which there is the presence of circular dolines of a maximum of 3 meters in diameter. For the determination of the mechanical properties of the reinforcement, the methodology proposed by Briançon and Villard (2007) was applied, having as a premise a surface deformation of, at most, 5%, whose results generated dimensioning abacuses to define the length parameters anchoring and traction effort of the geogrid. Numerical analyzes of the stress-strain type were performed to verify the level of strain related to the resistance of the foundation materials, considering the values obtained by the analytical method. The reinforcement by a geogrid set, for reinforcement and a woven geotextile, for physical separation, in elastoplastic regime, obtained resistance reduction factors (SRF) corresponding to the maximum surface deformations of 5%. The SRF obtained was consistent with good practices. It was observed that the deformations caused in the geosynthetics did not lead to their rupture.

Keywords: Karst Zone, Geosynthetics Reinforcement, Stress-Strain Analysis, Analytical Method.

1 INTRODUCTION

All voids in the ground constitute elements of weakness within a rock mass, and a karst zone is distinguished by having the largest natural voids, where the fault in the ceiling can create a significant geographical hazard. The natural consequence of progressive top failure is the upward migration of the voids, which can reach the surface where it causes instantaneous subsidence due to a cavity collapse (WALTHAM; BELL; CULSHAW, 2005).

According to Ford and Williams (2007), karst zones arise from the combination of high solubility in rock and well-developed secondary porosity. Also according to For and Williams (2007), approximately 20% of the Earth's continental surface, with the exception of the polar zones, is occupied by karst zones, and 20 to 25% of the world's population depends on the aquifers contained in these regions.

In view of the probability of doline formation in structural foundations, the methodology proposed by Briançon and Villard (2007) is used, which boils down to three steps: determination of the load applied to the geosynthetic, determination of the displacement of the geosynthetic, and determination of soil settlement. In addition to this analytical dimensioning, numerical modeling has been a useful tool to incorporate the differential behavior of elements subject to stresses and strains.

The present work aims to design the reinforcement of a hypothetical foundation in which there is a probability of dolinations, using geosynthetics, through the analytical methodology proposed by Briançon and Villard (2007), followed by its verification by stress-strain analysis made by a numerical model in the RS2 software (Rocscience).

2 ANALYTICAL METHODOLOGY

The structural design calculations of a hypothetical foundation, considering the occurrence of subsidence, were carried out based on the analytical methodology described by Briançon and Villard (2007). The general design procedure required to determine the mechanical properties of geosynthetic reinforcement includes (BRIANÇON; VILLARD, 2007):

1. determination of the load applied to geosynthetics, depending on the overload and the characteristics of the cover soil;
2. determination of the displacement of the geosynthetics, considering its membrane effect and its elongation in the anchorage areas;
3. determination of soil settlement, depending on its physical properties.

It should be noted that, at the junctions between the geosynthetic meshes, a minimum overlapping length is required. In this area, when a collapse occurs, the free ends of the geosynthetics and the weak friction of the interface lead to large deformations of the soil surface and reduction of the tensile forces acting on the geosynthetic compared to those obtained in the continuous section. In this way, the displacement of the soil surface is calculated in the overlapping sections and the maximum stresses are determined in continuous sections. The following sub-items describe the methodology proposed by Briançon and Villard (2007).

2.1 DETERMINATION OF APPLIED LOAD IN GEOSYNTHETICS

The load applied to the geosynthetic is calculated considering the cylindrical collapse of the soil over the cavity using the method proposed by Terzaghi (1943). Thus, through the geotechnical parameters for the foundation soils and the geometry of the subsidence, the applied load is calculated. The geotechnical parameters adopted for the reinforcement embankment, used for the calculation of the load on the subsidence and on the anchored areas are presented in the Table 1.

Table 1. Input data from the methodology of Briançon and Villard (2007).

Subsidence geometry	Circular	Subsidence geometry	Circular
L [m]	3	φ [°]	35
D [m]	3	C_e	1,1
p [kN/m]	20	k_a	0,27
γ [kN/m³]	20	Q [kPa]	47,68

2.2 BEHAVIOUR OF GEOSYNTHETICS ON SUBSIDENCE

The vertical displacements of the geosynthetic over the subsidence, linked to the membrane effect, result both from the application of load and from the horizontal displacement of the geosynthetic in the anchor zones, generating an increase in the length of the geosynthetic. Thus, in a continuous section where the highest stress is found, a relationship is established between the membrane effect of the geosynthetic, applied loads, geometry of the problem, soil characteristics and the geosynthetic. To do this, it is assumed that the reinforcement is unidirectional and the applied load is uniform. The required tensile stress of the geosynthetic is then calculated using Equation 1.

$$T_M = \frac{qL}{2\beta}\sqrt{1+\left(\frac{2\beta x}{L}\right)^2} \quad (1)$$

Let T_M the tensile force be at a point M, in N/m; q the vertical load above the subsidence, in kPa; L the length of the subsidence, in m; $\beta$the characteristic parameter of the change in orientation of the geosynthetic, at its starting point, and x the horizontal starting position of a point M, at m.

2.3 INFLUENCE OF THE CHANGE IN THE ORIENTATION OF THE GEOSYNTHETICS

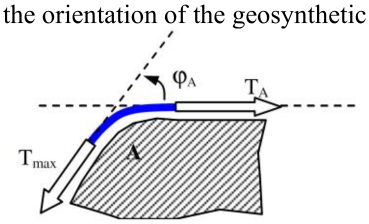
The change in the orientation of the geosynthetic, at the end of the subsidence, generates a reduction of the tensile stress in the geosynthetic, as illustrated in

Figure 1. This mechanism, represented by the characteristic parameter β, is calculated by interaction based on Equation 2 taking into account the

Figure 1.

$$\beta = tan\varphi_A \quad (2)$$

Figure 1. Influence of the change in the orientation of the geosynthetic (BRIANÇON; VILLARD, 2007).



2.4 GEOSYNTHETICS BEHAVIOR

In the anchorage area, three possible situations in a segment are verified (**Erro! Fonte de referência não encontrada.**) considering the horizontal displacement of the geosynthetic at the end of the subsidence, at the end of the geosynthetic, and corresponding to the maximum frictional stress.

On the other hand, in the overlapping sections, in addition to the friction between the soil and the geosynthetics, the friction between the geosynthetic meshes is considered. For this case, it is necessary to take into account the equations obtained to the left and right of the subsidence. Considering the limit equilibrium of a section and that the reinforcement is unidirectional and the applied load is uniform, we have the vertical deformation of the geosynthetic through Equation 5.

$$z_M = \beta \frac{x^2 - (L^2/4)}{L} \tag{3}$$

Being the z_M vertical displacement of the geosynthetics at a point M; L the length of the subsidence, in m; $\beta$the characteristic parameter of the change in orientation of the geosynthetic, at its starting point, and x the horizontal starting position of a point M, at m.

2.5 SURFACE DEFORMATION ASSESSMENT

The displacement of the surface is considered to be less than the vertical displacement of geosynthetics, due to the expansion of the soil during collapse or possible arching of stresses. Considering that the highest soil settlement above the subsidence is observed in the superposition condition of the geosynthetic, if the deformation of the soil and the geosynthetic are assumed to be parabolic, it is possible to find a relationship between the maximum displacement of the surface (s), geosynthetic maximum vertical displacement (s), expansion coefficient (C_e), and the height of the ground cover (H). This relationship is expressed by Equation 4 for a circular subsidence.

$$s = f - 2H(C| \quad |e - 1) \tag{4}$$

2.6 DETERMINATION OF ANCHORAGE LENGTH

The optimal anchoring length of geosynthetics (L_R) is defined as the length between the middle and the end of the geosynthetic plus the length required to sustain the tensile and deformation stress of the geosynthetic.

2.7 SIZING

The design of the reinforcement by geogrid type was carried out following the procedure proposed by Briançon and Villard (2007) for circular subsidence of 3 meters. Varying values were set for the following parameters: geogrid stiffness, geogrid deformation and protective embankment height, according to acceptable design values. Thus, corresponding values of surface deformation, anchorage length and tensile stress of the geosynthetic were calculated. It is noteworthy that the same procedure previously detailed was performed for circular subsidence of 2 meters and 4 meters, as a sensitivity assessment regarding the geosynthetic parameters.

The results are illustrated by the Figure 2 the Figure 6, which were used as abacuses for the design, with each curve representing a protective layer height.

As a premise, it was defined that the surface deformations should be minimal, so that a maximum surface deformation of 5 centimeters was established as the starting point of design. Thus, in the Figure 2 An economically viable stiffness of the geosynthetic was determined from the defined surface deformation of 5cm. A protective embankment of 2.5 meters was then found for a rigidity required for the geosynthetic of approximately 3,000 kN/m.

In Figure 3 The anchorage length of 5.5 meters was determined from the height of the embankment and the stiffness of the geosynthetics defined in the previous stage. In Figure 4 A tensile stress to the geosynthetic of 130 kN/m was established, based on the height of the embankment and the stiffness of the geosynthetic according to the first stage. Finally, in the Figure 5 It was found that the expected deformation in the geosynthetic is close to 5%.

Figure 2. Determination of geosynthetic stiffness and embankment height from 5% surface deformation.

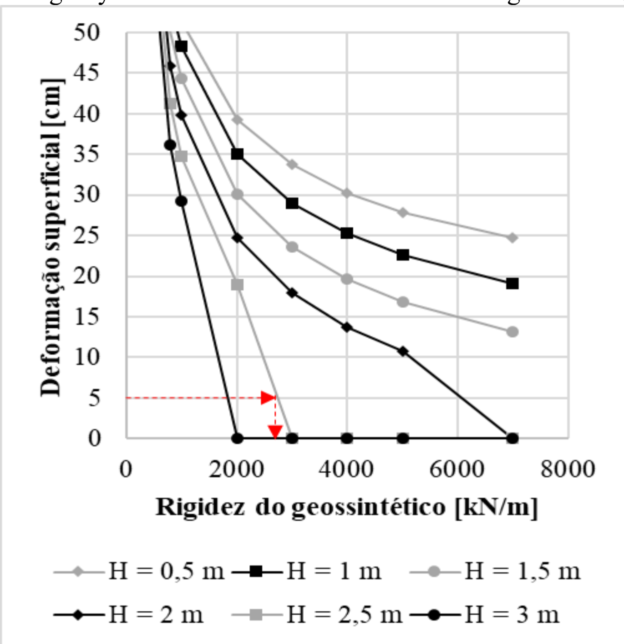


Figure 3. Determination of anchor length from the stiffness of the geosynthetic and the height of the embankment.

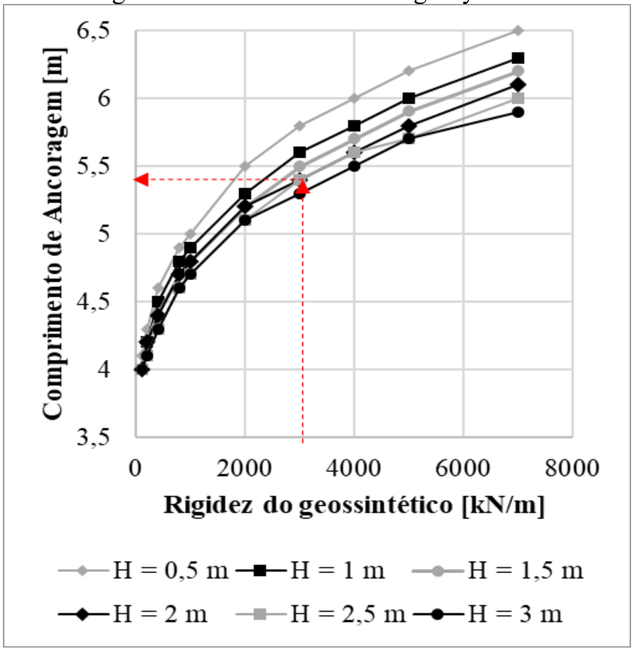


Figure 4. Determination of the tensile force of the geosynthetic from the stiffness of the geosynthetic and the height of the embankment.

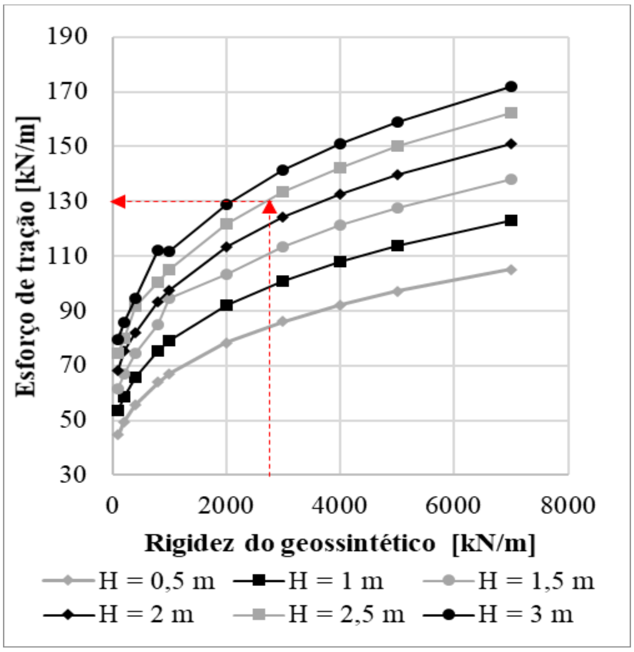
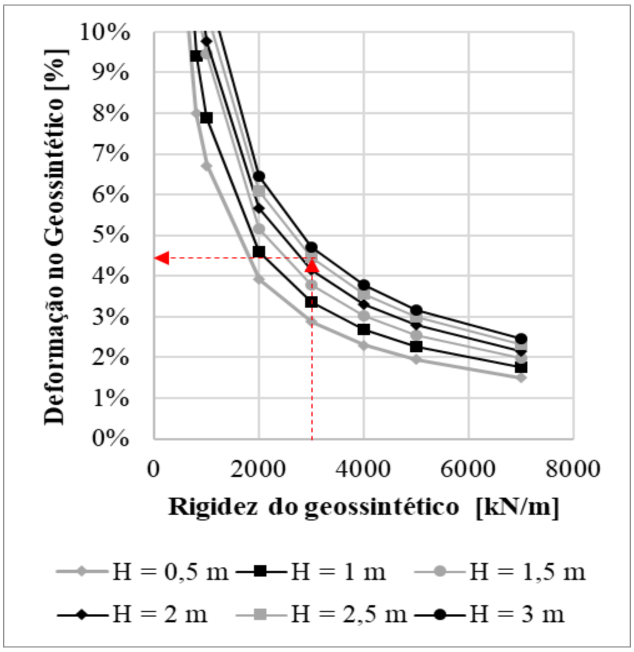


Figure 5. Determination of the deformation in the geosynthetic from the stiffness of the geosynthetic and the height of the embankment.



3 NUMERICAL MODELING

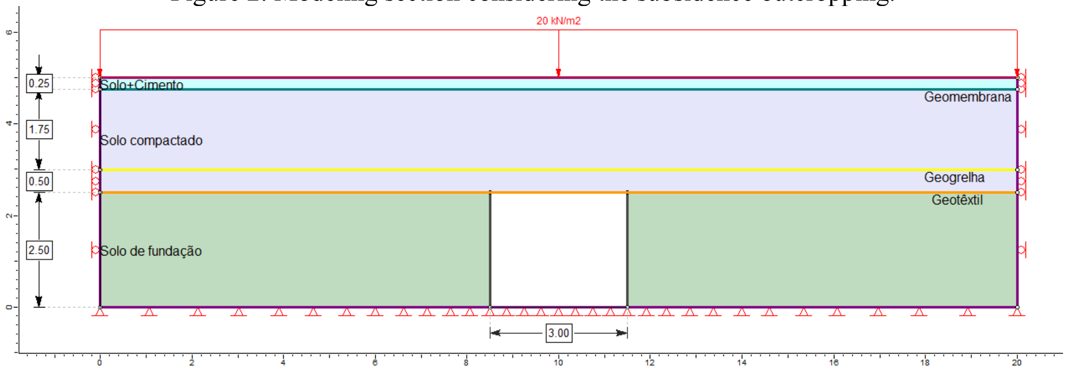
To verify the deformations and stress states in the foundation caused by the dolinations and resisted by the geosynthetics as dimensioned in item 2.4 by the methodology of Briançon e Villard (2007), two-dimensional stress-strain modeling was performed using the RS2 software version 2019 10.002 authored by ROCSCIENCE (2018).

3.1 ASSUMPTIONS OF THE ANALYSIS

As an initial premise of the modeling, the probability of natural occurrence of dolinamento is presented. The representative section, illustrated in the Figure 6, presents the geosynthetic reinforcement arrangement for stabilization of a hypothetical foundation with a circular subsidence of 3 m.

The formation of subsidence leads to the modeling of two representative instants of the case. A first instant in which the in situ condition is prior to the dissolution of the rock, in which the observed stratigraphy develops its confining stresses and vertical loads. In the second instant (Figure 6) The dissolution of the rock allows the insertion of the subsidence in this medium established by the conditioning loads of the first instant. It is noteworthy that for the representative model, the water table level was disregarded.

Figure 2. Modeling section considering the subsidence outcropping.



As a result of the safety assessment, the Shear Strength Reduction option was performed in RS2, which performs analyses of the stress-strain interaction by finite elements, in order to calculate a critical resistance reduction factor for each section. Therefore, the model does not seek to access the stability conditions, but to verify the level of deformation related to the strength of the foundation materials as opposed to the existence of subsidence.

3.2 MATERIAL PARAMETERS

The constitutive parameters and models adopted for the materials were based on those adopted for the development of the methodology by Briançon and Villard (2007). Like so The resistance parameters and elastoplastic behavior of the resistive materials in relation to dolinations were defined.

For the representative section, a foundation soil where the dolinamento is located was considered. The compacted soil represents the protective layer and the cement soil serves as protection for the geomembrane, as observed in the Table 2.

Table 2. Parameters adopted for soils.

Soil	Model	Parameters Category	Ei(MPa)	υ	C (KPA)	F (°)	□□ □°□	Y (kN/m³)
Compacted only	Plastic	Effective Voltages	7	0,30	10,0	35	35	20,00
Foundation soil	Elastic		20	0,30	10,5	35	-	20,00
Soil cement	Plastic		50	0,30	20,0	35	35	20,00

Geosynthetics were treated as structural lines in stress and strain modeling. It is noteworthy that the contact interface between geosynthetics and soil is considered a zone of fragility. Thus, a 70% reduction in resistance in these regions was considered in relation to the resistance of the soil in question. In this way, the Table 3 Presents the parameters associated with geosynthetics.

Table 3. Parameters adopted for geosynthetics.

Solo	Model	Tensile Modulus (kN/m)	Characteristic resistance (kN/m)	Residual resistance (kN/m)
Geogrid	Plastic	3000	130	100
Geomembrane	Elastic	100	-	-
Geotextile	Plastic	400	100	100

3.3 RESULTS OF NUMERICAL MODELING

According to Waltham, Bell and Culshaw (2005), when it comes to subsidence, values corresponding to safety factors are around 5, by analogy, the value found as SRF is consistent with what is indicated by good practices as observed in the Figure 8. For the SRF close to 5, there are deformations of 6 to 7 cm (Figure 7), close to 5 cm of the analytical design (item).

It is also possible to observe the displacements of the geosynthetics, represented by lower and upper bars along their length, caused due to the tensile loads due to the presence of subsidence. The Figure 8 illustrates the sliding of the geomembrane, geotextile and geogrid in relation to the contact soils. It was verified that the tensile stress did not lead to the rupture of these elements, with displacements in the order of 10 cm close to the subsidence and millimeters at the extremities.

Figure 7. Convergence for SRF variation at shear for 3m subsidence.

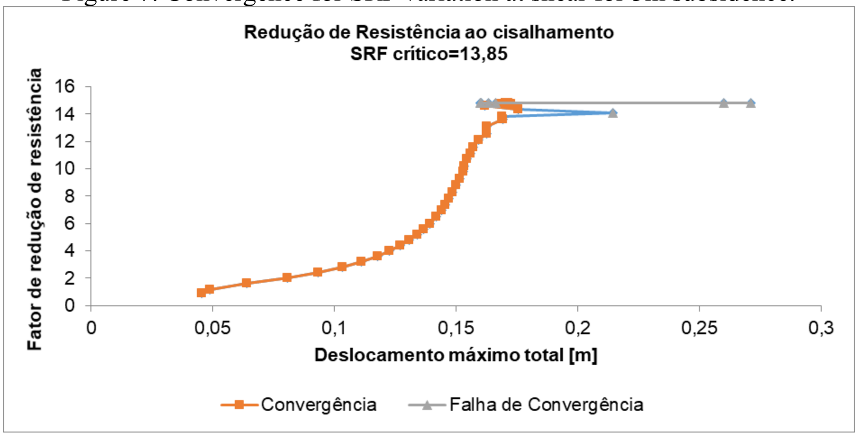
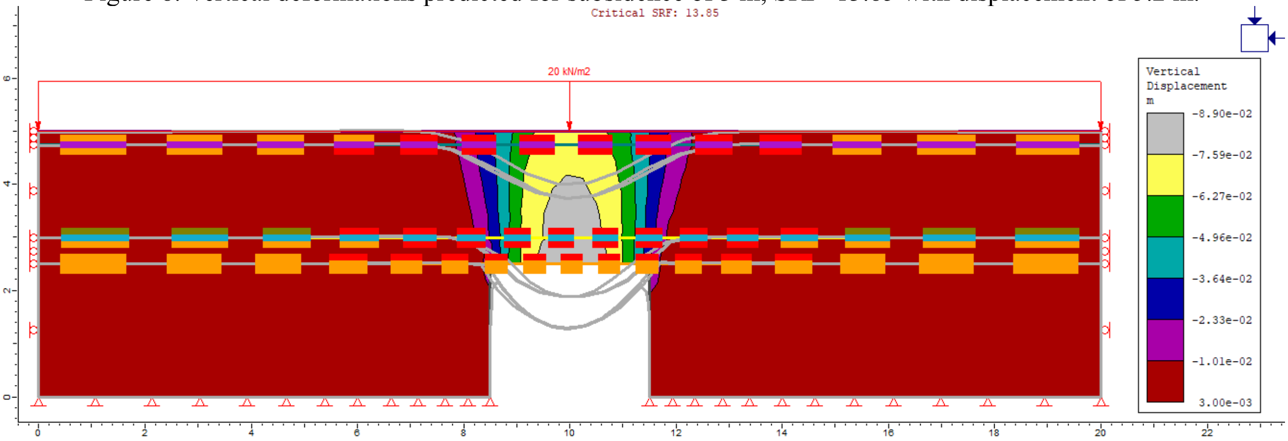


Figure 8. Vertical deformations predicted for subsidence of 3 m, SRF=13.85 with displacement of 5.2 m.



NOTE: The bars along the geosynthetics represent their slippage relative to the contact soils.

4 CONCLUSION

The reinforcement design of a hypothetical foundation with probability of dolinations was presented, using geosynthetics, through the analytical methodology proposed by Briançon and Villard (2007). Verification is made by stress-strain analysis made by numerical model in RS2 software (Rocscience).

The analytical and numerical methodologies showed levels that meet the reinforcement of a foundation conducive to dolinations of up to 3 meters in diameter, in relation to a surface deformation of 5%. However, such dimensioning does not prevent the outcropping of larger sinkholes. Therefore, a risk analysis is recommended to map the cavities and validate the expected diameter of subsidence in non-hypothetical cases.

Therefore, the methodologies described present good adherence to the behavior of the proposed system for the emergence of subsidence of up to 3 m in diameter on the surface.

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