Applications and Modeling of Geosynthetics in Highway Infrastructure

Lizeth Ardila Montilla[1](✉), Cristina Schmidt[1], André Estêvão Silva[1], Carlos M. Rodriguez[2], and Trevor Walker[2]

[1] Huesker Ltda, Sao Jose Dos Campos, Brazil
lizeth.ardila@huesker.com.br
[2] Huesker Inc, Charlotte, NC, USA

Abstract. Although there is already a significant and consolidated experience by the technical community responsible for highway infrastructure projects, which includes large and important projects implemented with different geosynthetic solutions, there are still gaps in knowledge that can be better answered. Two of these gaps are highlighted in this paper: the most appropriate tools and methodologies for geosynthetic modeling analysis and the most relevant parameters of these materials to be considered. The objective of this study is to present these kinds of solutions, including geogrids, geotextiles and geocomposites, highlighting their geotechnical approach. In addition, the relevant factors in the design and dimensioning of these applications will be highlighted, including calculation assumptions, analysis methods with limit equilibrium (Slide) and stress-strain (RS2 and RS3) numerical models. Finally, the article points out some of the most current technical reflections in the context of the subject in question, the design and implementation of highway structures.

Keywords: Geosynthetics · Highway Infrastructure · Slope Stability · Pavement · Soft Soils

1 Introduction

The use of geosynthetics has been evidenced for at least 30 years as an efficient alternative in the development of highway road infrastructure because of its versatility, high variety of solutions and good performance. In this context, geosynthetics are employed as a solution in different components of the highway infrastructure including slope stability reinforcement, slope protection, bridge abutment construction systems, structural pavement reinforcement or rehabilitation, soft soil stabilization, among several other applications.

In this paper the most common applications of geosynthetics used in the development of highway infrastructure will be presented, highlighting the use of geogrids, geotextiles and geocomposites. Subsequently, a series of considerations in the modeling of these structures will be addressed, pointing out the main assumptions and design aspects.

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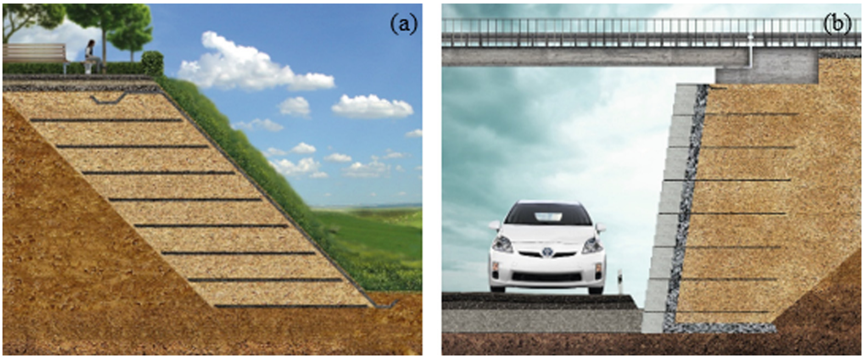


Fig. 1. Application slope stability (a) Slope reinforcement (b) Bridge Abutment—Huesker.

2 Applications

2.1 Slope and Soil Reinforcement

Geogrids can act as a structural soil element ensuring the internal stability of steeply sloping earth massifs on adjacent slopes, retaining walls, bridge abutments and viaducts, which can be constructed quickly and with local soil.

Geogrids work in multiple layers as internal stabilization elements in compacted soil masses. This type of work has traditional methods of design in the literature, as well as construction systems designed specifically for this purpose. The most typical applications are illustrated in the Fig. 1.

Different experiences have been reported in the literature with the use of geosynthetics for slope stabilization in road infrastructure, among them Alexiew *et al* (2016) demonstrating the long-term efficiency of this type of solutions, Torre *et al* (2006) highlighting the stabilization of slopes with vegetated faces, Guler *et al* (2011), Poggi and Russo (2019) evidencing the good performance even during seismic stresses, and Silva (2006) describing the use and application for bridge abutments.

2.2 Soil Foundation Stabilization

Ensuring the stability condition of embankments supported on soils with low bearing capacity is a challenge for the development and operation of infrastructure works located in regions with predominantly soft soil. Geogrids, geotextiles and geocomposites can serve as a solution, ensuring that no problems related to embankment failure of road infrastructure occur throughout the life of the project.

Geogrids or geotextiles can guarantee the overall stability of the embankment built on low-capacity soils, with or without vertical drains, avoiding the need for soil removal or construction of equilibrium berms.

Another reinforcement system can be constituted from geosynthetic encased columns, GECs, which perform the confinement and reinforcement of granular material in sand or gravel columns, ensuring higher load capacity and lower deformability of the

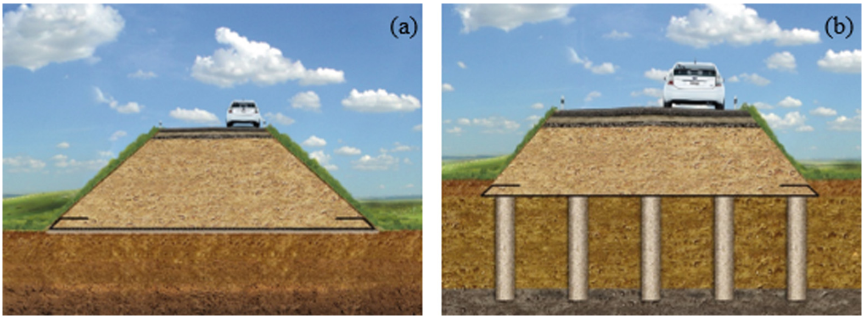


Fig. 2. Application foundation treatment (a) Soft soil Embankment (b) Geosynthetic encased columns—Huesker.

columns in a high-performance soft soil improvement system for the stabilization of infrastructure embankments. The most typical applications are illustrated in the Fig. 2.

The experience in the application of geosynthetics for soft soil treatment has been described by different authors, highlighting calculation methods, application innovations, numerical analysis, etc. Some reference studies are Mello *et al* (2002), Ruiz *et al* (2010), Alexiew *et al* (2013) and Ruiz *et al* (2013).

Regarding the specific use of cased columns for ground improvement, several case studies applied to road infrastructure have been retrieved, highlighting premises and generalities of the project, application perspectives and instrumentation methods, among them, Dimiter *et al* (2012), Sobolewski *et al* (2012), Alexiew *et al.* (2014), Guler *et al* (2014) and Schnaid *et al* (2017).

2.3 Structural Pavement Reinforcement or Rehabilitation

Geogrids are placed as reinforcement in layers of the paving structure (base or subbase) and act as a kind of subgrade reinforcement when the subgrade has low resistance. In this case, bidirectional, high initial stiffness modulus geogrids (high stiffness modulus at low strain levels) are designed to perform two primary functions: act as a membrane to prevent rutting at the sidewalk surface due to the base of the sidewalk punching into the subgrade; and act as a confining element of the base layer to prevent subgrade rutting. The most typical applications are illustrated in the Fig. 3.

In addition, geogrids can be used as asphalt reinforcement in restoration work on cracked rigid or flexible sidewalks, preventing the propagation of cracks by reflection to the new overlay, enabling the intervention to be done quickly and without interrupting the road. On the other hand, Geotextiles act as a reinforcement element for the base layers of coated or uncoated road sidewalks, increasing the CBR and reducing sidewalk deformations, or even making it possible to use less competent materials.

Some experiences of this type of application are described by Carmo *et al* (2012), Junior et al (2011), and Thesseling *et al* (2013).

Fig. 3. Application pavement reinforcement—Huesker

2.4 Slope Protection

Reinforcing geogrid with a three-dimensional structure offers a combination of reinforcement and erosion control and facilitates vegetation on steep slopes. Optional planting of vegetation creates structures with an aesthetically pleasing natural appearance. This type of geogrid guarantees the stability of the cover material, preventing slippage due to lack of adherence of this layer to the steep slope, improving the effectiveness of the vegetation work. The application is described in more detail by Russo *et al* (2008). The applications are illustrated in the Fig. 4.

3 Modeling Considerations

The role of geosynthetics in the geotechnical modeling of road infrastructure components is generally to provide soil reinforcement in the structure under analysis, in retaining walls, earthworks on soft soils, bridge abutments, among others. Thus, the main types of geosynthetics modeled are geogrids and woven geotextiles. The most common analyses during the design of these structures are stability analysis and stress-strain analysis. The main considerations to be taken into account during the modeling of geosynthetics for highway infrastructure are described below.

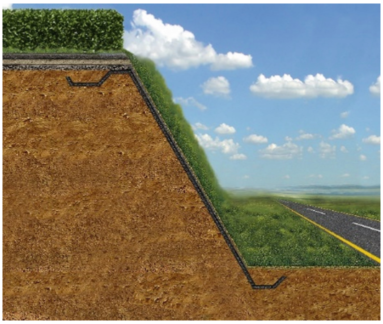


Fig. 4. Application slope protection—Huesker

3.1 Stability Analysis

The stability analyses in geotechnical simulations are commonly carried out by software using limit equilibrium. The geometry of the problem must be introduced and define the kind of loads that will be required in the study, for example, dead loads and live loads operating the geotechnical structure. In addition, analysis scenarios must be established in accordance with the project specifications and analytical calculations required by design standards, for example, static scenarios, seismic scenarios, operational scenarios, and the possibilities required for each project premises.

To evaluate the safety in the models, stability analyses can be performed using methods of analysis, based on the Limit Equilibrium theory: Bishop Simplified, Morgenstern-Price, Spencer, Janbu, Felleneus, Sarma and others.

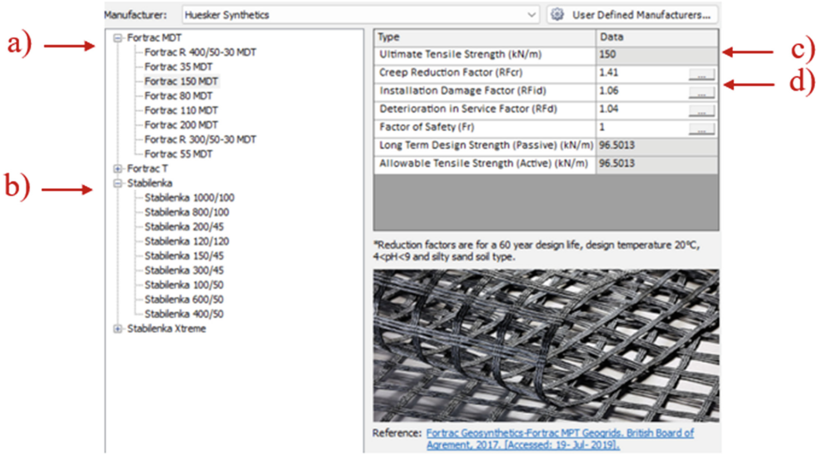
In these kinds of analyses were sought circular and non-circular potential rupture surfaces to search for the lowest factor of safety (FoS). According to Gerscovich (2016) the rupture surface tends to be circular in relatively homogeneous soils, while exhibiting a flatter appearance in the occurrence of a more significant anisotropy in relation to strength. Non-circular analyses were considered at the global rupture surface level, due to intercalations of materials, which may result in a plane of weakness. At the local level, the ruptures present themselves within the same soil layer (homogeneous massif), thus tending toward a circular rupture surface.

Regarding soil properties, the characteristics of the relevant lithotypes and materials must be defined. Characteristics such as shear strength, specific gravity and water surface are entered into the software.

For geosynthetic properties, Slide software has a detailed library of geosynthetic characteristics for reinforcement. The library contains data for Huesker geosynthetics. These characteristics are explained below, according to the Fig. 5.

a) Geogrids: The library contains different kind of geogrids. Some types of soil reinforcement geogrids are made of low creep polyester yarns coated with a polymer coating. Other type of soil reinforcement mesh is made of alkali-resistant polyvinyl alcohol (PVA) fibers with a low creep tendency and a polymeric protective coating.
b) Geotextiles: The library exhibits geotextiles, for example PET (polyethylene terephthalate) and PVA.
c) Ultimate tensile strength: It is the maximum nominal tensile strength of the geosynthetic, according to ISO 10.319 or ASTM D-6337 tests.
d) Reduction factors: In addition to the strength of the geosynthetic, other effects that may reduce the strength of the material must be considered. This consideration is done by means of reduction factors. The considered factors are creep reduction factor, reduction factor for installation damage, reduction factor for weathering, including exposure to ultraviolet light, factor for chemical/environmental effects and a factor of safety for the extrapolation of data. It should be noted that the design strength should be compared with the strength obtained after application of the reduction factors.

It should be noted that the above-mentioned library is a facility presented by the Slide software. To model geosynthetics that are not in the library, the considerations mentioned in the previous paragraph must be considered in order to enter their characteristics, based on the manufacturer's characterization.



Manufacturer: Huesker Synthetics

Type	Data
Ultimate Tensile Strength (kN/m)	150
Creep Reduction Factor (RFcr)	1.41
Installation Damage Factor (RFid)	1.06
Deterioration in Service Factor (RFd)	1.04
Factor of Safety (Fr)	1
Long Term Design Strength (Passive) (kN/m)	96.5013
Allowable Tensile Strength (Active) (kN/m)	96.5013

*Reduction factors are for a 60 year design life, design temperature 20°C, 4<pH<9 and silty sand soil type.

Reference: Fortrac Geosynthetics-Fortrac MPT Geogrids, British Board of Agrement, 2017, [Accessed: 19- Jul- 2019].

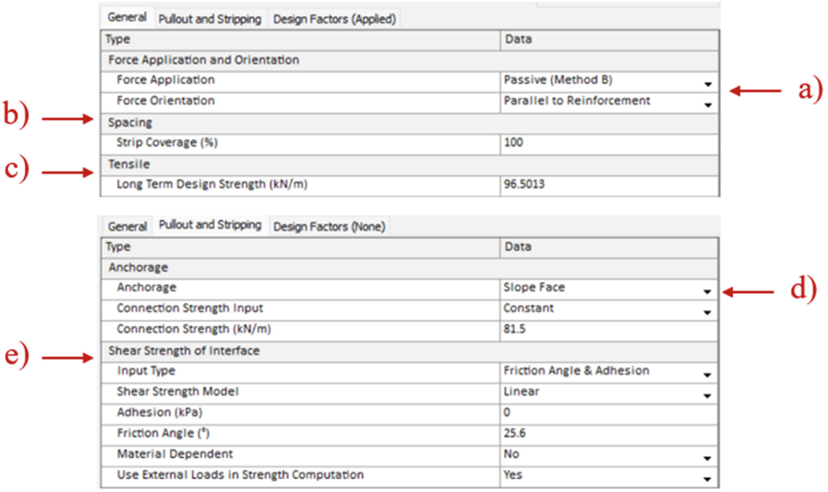
Fig. 5. Huesker Geosynthetic Properties in Rocscience software

Subsequently, the dimensional and strength properties of the reinforcement, presented below, according to the Fig. 6, must be input:

a) Force application: generally for geosynthetics, the passive method is used, because the material isn't subject initially to tensioning, and the force acts parallel to the reinforcement.
b) Spacing: The Strip Coverage refers to the spacing of the reinforcement strips, in the Out of Plane direction. The 100% Strip Coverage means that the reinforcement is continuous, without spacing. If the reinforcement has spacing in this direction, the percent of coverage is calculated by dividing the sum of the width of the strip and the space considered.
c) Tensile: Is the maximum capacity of load of the reinforcement, according with the manufacturer's characterization or with the manufacture's library. This tensile is the design tensile.
d) Anchorage: It depends on the type of anchorage that the geosynthetic has, it can be anchored on the face, embedded, anchored on both edges, or without anchorage.
e) Shear Strength of interface: The strength of the interface can be considered as a fraction of the resistance to deformation of the soil where it is inserted, or from pullout tests.

For illustrative example, the Fig. 7 shows the numerical modeling with Slide software of a reinforced soil wall used in highway infrastructure.

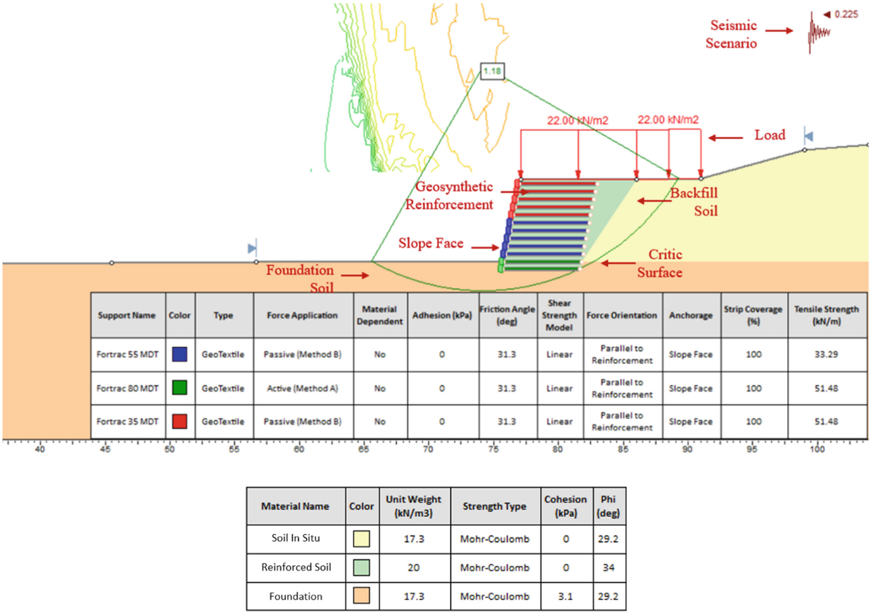
Note that the model consists of the minimum infrastructure components required in the construction system, including, foundation soil, backfill soil, modeled geosynthetic reinforcement and loads attributed to the bearing structure. For the geosynthetic reinforcement, the table of properties adopted in the model is presented. In this case, a seismic scenario evaluated in the project is also shown. The figure also presents the critical safety factor obtained for the analysis scenario.



Type	Data
Force Application and Orientation	
Force Application	Passive (Method B)
Force Orientation	Parallel to Reinforcement
Spacing	
Strip Coverage (%)	100
Tensile	
Long Term Design Strength (kN/m)	96.5013

Type	Data
Anchorage	
Anchorage	Slope Face
Connection Strength Input	Constant
Connection Strength (kN/m)	81.5
Shear Strength of Interface	
Input Type	Friction Angle & Adhesion
Shear Strength Model	Linear
Adhesion (kPa)	0
Friction Angle (°)	25.6
Material Dependent	No
Use External Loads in Strength Computation	Yes

Fig. 6. Support proprieties in Slide-Rocscience



Support Name	Color	Type	Force Application	Material Dependent	Adhesion (kPa)	Friction Angle (deg)	Shear Strength Model	Force Orientation	Anchorage	Strip Coverage (%)	Tensile Strength (kN/m)
Fortrac 55 MDT	🟦	GeoTextile	Passive (Method B)	No	0	31.3	Linear	Parallel to Reinforcement	Slope Face	100	33.29
Fortrac 80 MDT	🟩	GeoTextile	Active (Method A)	No	0	31.3	Linear	Parallel to Reinforcement	Slope Face	100	51.48
Fortrac 35 MDT	🟥	GeoTextile	Passive (Method B)	No	0	31.3	Linear	Parallel to Reinforcement	Slope Face	100	51.48

Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)
Soil In Situ	🟨	17.3	Mohr-Coulomb	0	29.2
Reinforced Soil	🟩	20	Mohr-Coulomb	0	34
Foundation	🟧	17.3	Mohr-Coulomb	3.1	29.2

Fig. 7. Numerical model in Slide—Retaining wall

3.2 Stress Strain Analysis

The stress-strain numerical analyses in geotechnical simulations, including structures integrating geosynthetic elements, are commonly carried out by software using finite element, finite differences, or discrete element methods. As in limit equilibrium analysis, the geometry of the problem, required loads and analysis scenarios must be established in accordance with the project specifications and analytical calculations required by design standards.

Regarding the material properties, in addition to the shear strength parameters, the deformability parameters of each material must be introduced. Although the most typical approach is the Mohr Coulomb elastic-plastic failure envelope (constant stiffness), to characterize soil deformability the literature offers different constitutive models depending on the nature of the foundation, landfill or backfill soil under consideration (Lade, 2005). The stress strain behavior of the soil constitutive models can be calibrated by simulation and comparison of triaxial compression tests or instrumented monitoring of existing structures. The other components of the road infrastructure systems mentioned in this article, e.g., concrete blocks, concrete panels, accessories, and even the geosynthetics themselves, are usually modeled as elastic materials.

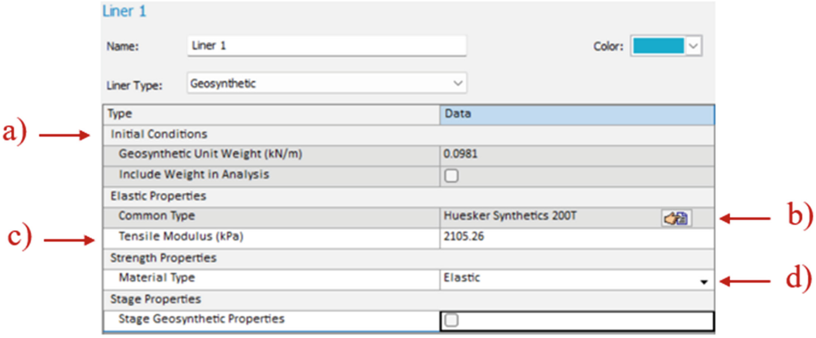
The models are generally made in the plane-strain condition, due to the constant cross-section geometry that characterizes highway infrastructure project. However, in situations where the geometry rotationally symmetric about an axis, axisymmetric modeling condition can be used.

Other fundamental aspect are the boundary conditions considered in the model, which are those field conditions of full knowledge or analysis assumptions that allowed the estimation of the calculations of the mechanical variables. Therefore, total or partial restrictions can be adopted on the laterals and base of the model, or displacements can be imposed on the model boundary.

A recommended practice in infrastructure modeling for stress-strain analysis is the simulation of the construction and operation stages. These stages should include the structuring of soil layers, application of compaction loads, simulation of dead loads, simulation of live loads and simulation of extraordinary loads (Ardila *et al*, 2022; Ardah *et al*, 2017; Ruiz *et al*, 2013; Ehrlich *et al*, 2012), with the objective of having more realistic models that allow to obtain performance responses of such structures.

Regarding the properties of the geosynthetics, for the specific case in the RS2 and RS3 software. In the stress-strain analysis, additional parameters are required, described in Fig. 8 and explained below:

a) Initial conditions: the software allows the inclusion of the own weight of the geosynthetic and gives the option to include this weight during the analysis process. This own weight comes from the library or can be found in the geosynthetic datasheet.
b) Type of geosynthetic: the software provides a library containing the strength characteristics, as well as the reduction factors for geogrids or geotextiles, as presented in the limit equilibrium item. In this section the geosynthetics to be used are defined.
c) Tensile Modulus: refers to the modulus of stiffness of the geosynthetic required at the level of deformation required by the project. These values are obtained from the stress-strain curves of the material and are generally available in the datasheet. According to ISO 10.319 or ASTM D-6337 tests. The deformation analyzed is generally between 2% to 10%, depending on the type of geosynthetic polymer and the project application.



Liner 1

Name: Liner 1

Color: 🟦

Liner Type: Geosynthetic

Type	Data
Initial Conditions	
Geosynthetic Unit Weight (kN/m)	0.0981
Include Weight in Analysis	☐
Elastic Properties	
Common Type	Huesker Synthetics 200T
Tensile Modulus (kPa)	2105.26
Strength Properties	
Material Type	Elastic
Stage Properties	
Stage Geosynthetic Properties	☐

Fig. 8. Liner proprieties in RS2 and RS3-Rocscience

d) Strength Properties: geosynthetics can be modeled with elastic or plastic constitutive model establishing the peak strength and residual strength of the material. Additionally, properties can be considered in specific stages of the numerical model.

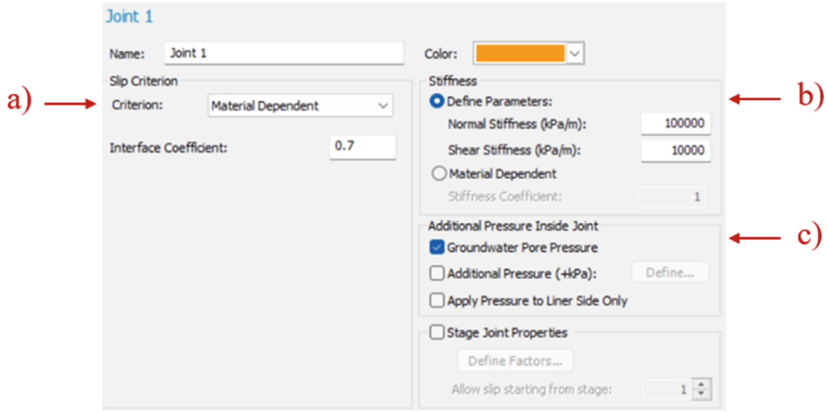
The geosynthetic elements in the model can be included directly as a liner element or as a structural interface. The liner is a continuous element, which in the case of application as a geosynthetic has hardly any tensile strength (no compressive strength, no flexural strength). The structural interface is a combination of liner and joints that allow to characterize the sliding phenomena between the geosynthetic and the soil.

In the case of considering the geosynthetic as a structural interface, the characterization of the joint will be of great importance in the performance of the numerical model. The properties that can be analyzed are described below:

a) Joint Slip criterion: The software allows to model the slip at joints of different criteria. The most used criteria for modeling interface with geosynthetics are Material Dependent, Mohr Coulomb, Geosynthetic Hyperbolic. The Material Dependent criterion establishes an interface coefficient that attributes a proportion of the soil strength to the joint, this proportion is generally between 0.7 to 0.9, depending on the characterization of the geosynthetic reinforcement. The Mohr Coulomb criterion allows direct input of the shear strength parameters at the joint, which can be obtained from the soil strength parameters, or from direct shear testing. The Geosynthetic Hyperbolic criterion can be calculated from the correlation of Esterhuizen, Filz and Duncan (2001) that characterize the shear strength of soil and geosynthetic interfaces with the definition of the adhesion and friction angle parameters.

b) Joint Stiffness: The relative interface movement is controlled by interface stiffness values in the normal and tangential directions. These values can be obtained by correlations with the material stiffness or physical tests, as presented by Hatami and Bathurst (2005). If this data is not available, there is also the option of entering a stiffness coefficient.

c) Additional pressure inside joint: Additional considerations can be included in the joint to model additional pressures, permeability, joint activation at specific stages of the model construction, among others (Fig. 9).



Joint 1

Name: Joint 1

Color:

Slip Criterion

Criterion: Material Dependent

Interface Coefficient: 0.7

Stiffness

● Define Parameters:

Normal Stiffness (kPa/m): 100000

Shear Stiffness (kPa/m): 10000

○ Material Dependent

Stiffness Coefficient: 1

Additional Pressure Inside Joint

☑ Groundwater Pore Pressure

☐ Additional Pressure (+kPa):

☐ Apply Pressure to Liner Side Only

☐ Stage Joint Properties

Allow slip starting from stage: 1

Fig. 9. Joint proprieties in RS2 and RS3-Rocscience

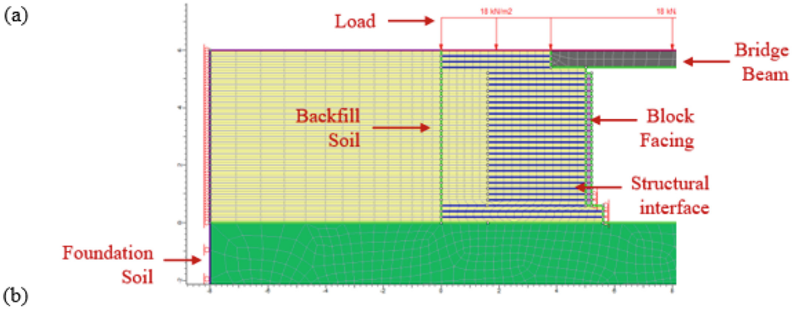
In general, the results that are evaluated in the stress-strain analyses according to the expected performance of the project are horizontal displacements in faces or slopes and vertical displacements in the infrastructure surface verifying admissible deformations and settlements, deformations in the reinforcement and maximum forces in the reinforcement to verify the strength of the geosynthetic, stress distribution and maximum shear deformations to evaluate areas and rupture surfaces that require special attention.

For illustrative example, the Fig. 10 shows the numerical modeling with RS2 software of a Bridge Abutment used in highway infrastructure. Note that the model consists of the minimum infrastructure components required in the construction system, including, foundation soil, backfill soil, geosynthetic reinforcement modeled as structural interface, block face, bridge deck and loads attributed to the load-bearing structure. The figure also presents the results obtained in the model, specifically as a function of the vertical and horizontal displacements of the structure.

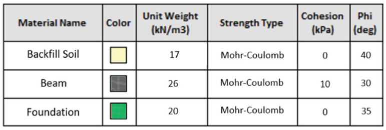
4 Conclusions

In this paper were presented the most common applications with geosynthetics and the main considerations in numerical modeling with Rocscience software. The main conclusions are presented below:

- The geogrids, geotextiles and geocomposites are elements of great versatility, and vital to constructing robust infrastructure projects in a timely way.
- Soil characteristics (soil, foundation, in situ), performance indicators (deformations, displacements, safety factor), geometry, scenarios and applicant loads are among the main items that must be considered during the application of geosynthetics in road infrastructure projects.
- The properties of the geosynthetic and its input in the software analysis, both stability and stress-strain, must be accurate with respect to the manufacturing data, as is the case for the consideration of reduction factors in geosynthetic reinforcement. The omission of these considerations can lead to insufficient and unsafe designs.



(b)



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)
Backfill Soil	🟨	17	Mohr-Coulomb	0	40
Beam	⬛	26	Mohr-Coulomb	10	30
Foundation	🟩	20	Mohr-Coulomb	0	35

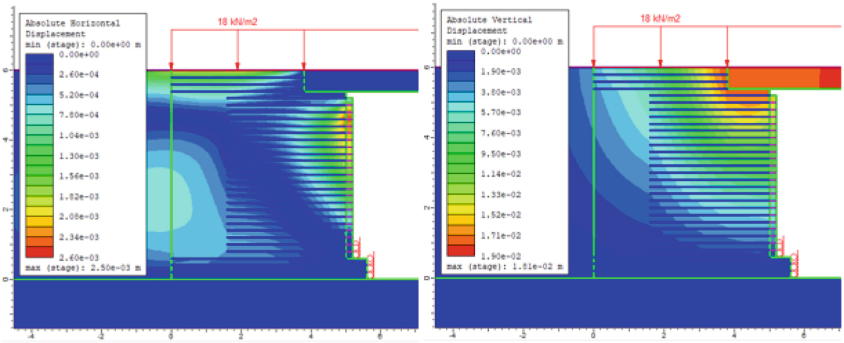


Fig. 10. Numerical model in RS2—Bridge Abutment

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