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Stability assessment around a railway tunnel using terrestrial laser scanner data and finite element analysis

Evaluación de la estabilidad alrededor de un túnel ferroviario usando los datos de un escáner láser y el análisis de elementos finitos

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Abstract

Geotechnical analysis of tunnels in complex geo-structural environments requires an advanced understanding of the inter-block structure effect on rock mass behavior, such as joints and fractures systems, bedding and foliation planes, among other discontinuity types. The conventional approach for preliminary geotechnical analysis of tunnels is based on a continuous-equivalent system representation of rock mass, i.e. without explicit consideration of systematic discontinuity systems. However, to obtain a closer to reality results of the rock mass expected behavior, geo-structural data should be included from the initial stage of geotechnical analysis. A case study is used to analyze the implications of the discontinuity systems inclusion on the rock mass stability around tunnel. Two-dimensional finite element numerical models were developed using three different models to the generation of rock discontinuity systems. The obtained results show that fracture intensity parameter help to generated more realistic two-dimensional DFNs.

Keywords: *Tunnel; TLS; FEM; DFNs*

Resumen

El análisis geotécnico de túneles en ambientes geo-estructurales complejos requiere de una comprensión avanzada del efecto producido por las estructuras interbloque sobre el comportamiento del macizo rocoso, como los sistemas de juntas y fracturas, los planos de estratificación y foliación, entre otros tipos de discontinuidades. El enfoque convencional de un análisis geotécnico preliminar de los túneles se basa en la representación de un sistema continuo-equivalente del macizo rocoso, es decir, no se consideran explícitamente los sistemas de discontinuidades sistemáticas. Sin embargo, para obtener resultados más realistas del comportamiento esperado del macizo rocoso, se deberían incluir los datos geo-estructurales en la etapa inicial del análisis geotécnico. Se usó un estudio de caso para analizar las implicancias de la inclusión de los sistemas de discontinuidades sobre la estabilidad del macizo rocoso alrededor de un túnel. Se desarrollaron modelos numéricos de elementos finitos bidimensionales usando tres modelos diferentes para generar los sistemas de discontinuidades de la roca. Los resultados obtenidos muestran que el parámetro intensidad de la fractura ayuda a generar mallas de fractura discreta (DFN) bidimensionales más realistas.

Palabras clave: Túnel; TLS; FEM; DFNs

1. Introduction

The construction of geologically realistic discontinuity system networks to use in the geomechanical evaluation of underground excavations has gained ground over the conventional techniques of considering rock mass as a continuous equivalent material and the geomechanical classification systems based on empirical data. Currently the discrete fracture networks are the technique that is mainly used. It offers the possibility of maximizing the use of geo-structural data collected via manual geotechnical mapping or remote sensing techniques, like digital photogrammetry and laser scanning (Elmo et al., 2014).

(Cacciari and Futai, 2017) have presented a methodology for tridimensional numerical simulations of tunnels excavated in discontinuous rock masses, based on the terrestrial laser scanner technique (TLS) and the generation of discrete fracture networks (DFNs). These authors have discussed several aspects related with the mapping of discontinuities using TLS, statistical analysis of discontinuities using window sampling methods and tridimensional numerical modeling using DFNs.

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The construction of underground excavation projects is often made in rock masses with discontinuity systems such as failures, stratification planes and foliation, seams and fractures, among others. These discontinuity systems induce the formation and instability of rock blocks and wedges during the execution and operation stages of underground works. The discontinuity systems usually occur in packages, which can be geometrically described by their orientation, trace length, persistence and spacing. In addition, the low and sometimes non-existent resistance to the cross-section of the discontinuity systems, high levels of tension in situ, as well as the confinement loss conditions during the execution of the excavations, induce different modes of instability and the failures of rock blocks formed by the intersection of two or more discontinuity systems, such as sliding, toppling and falls or collapses within the excavation.

To study the effect of the inclusion of geo-structural data on the stability of underground excavations built in discontinuous rock masses, a 10-m long section of the Monte Seco tunnel, located in the Southeast of Brazil, has been used as a case study. For this, two-dimensional numerical simulations considering a semi-discontinuous elasto-plastic means have been made using the FEM-RS2 finite element commercial software (Rocscience, 2015).

In the numerical simulations which explicitly consider rock mass discontinuity systems, three discontinuity network generation methodologies have been evaluated, namely: deterministic parallel, statistical parallel and the Baecher empirical model (Rocscience, 2015); (Baecher et al., 1977). This was done by directly importing the entry parameters, which in this case, correspond to TLS measurements of the discontinuity system's geometrical parameters. In this way, discontinuity planes are created, defined by their specific geometric characteristics, which, at the same time, generate two-dimensional networks of the discontinuity systems coupled to the finite elements model.

The results obtained show and highlight the significant effect of the explicit modeling of discontinuity systems over the stress-displacement patterns around the studied tunnel, being able to quantitatively visualize the effects on the concentration and relaxation of stresses, shear zones, the formation of blocks and the displacement trajectories. In addition, the over-excavation profiles obtained using the numerical modeling have been compared with TLS measurements, through which a good fit with the onsite observations has been obtained.

2. Methodology

Numerical simulations of rock tunnels must consider the complexities related to the interaction of three-dimensional tunnel geometry and true geometrical discontinuity system (i.e., orientation, trace length, persistence and spacing). Discontinuity systems are usually represented deterministically without accounting for uncertainty and spatial variability which represent inherent characteristics of rock mechanics problems (Einstein and Baecher, 1983). Terrestrial remote sensing techniques (e.g., digital photogrammetry and laser scanning) now provide a convenient additional tool to help reduce these problems. The remote sensing data provides key geotechnical information such as discontinuity orientation and length as well as the location of each discontinuity measurement.

The volume of data can be significantly greater both in terms of magnitude and the areal extent mapped compared to traditional geotechnical data mapping (Fekete and Diederichs, 2013). The acquired discontinuity data can be used to develop stochastic DFNs for a more realistic representation of discontinuity systems (Havaej et al., 2016). The application of remote sensing methods for discontinuity mapping has increased significantly in the last decade. There are several applications of remote sensing techniques in rock engineering practice, such as rock mass characterization (Tonon and Kottenstette, 2006); (Ferrero et al., 2009); (Lato et al., 2009), (Lato et al., 2010); (Gigli and Casagli, 2011); (Lato et al., 2013); (Otoo et al., 2013); (Deliormanli et al., 2014); (Lai et al., 2014), rock slope stability (Strouth et al., 2006); (Ghirotti and Genevois, 2007); (Sturzenegger and Stead, 2009); (Lato and Vöge, 2011); (Lato et al., 2012); (Lato et al., 2015); (Tuckey and Stead, 2016) and underground excavations (Fekete et al., 2010); (Styles et al., 2010); (Fekete and Diederichs, 2013); (Lato and Diederichs, 2014); (Preston et al., 2014); (Walton et al., 2014); (Cacciari and Futai, 2017); (Delaloye et al., 2015); (Villalobos et al., 2017).

DFNs have been used in a wide range of geomechanical problems (e.g., open pits, tunneling, block caving, reservoir geomechanics, etc.). In order to define a fracture network to represent a natural discontinuity system, (Elmo, 2006) proposed that at least three sets of parameters are required: fracture size distribution, fracture orientation distribution and fracture density. (Dershowitz et al., 2014) defining two different parameters, the areal intensity P21 and volumetric intensity P_{32}, to represent the degree of fracturing in rock masses. P_{21} and P_{32} are defined as the cumulative length of fractures per unit area and the cumulative area of fractures per unit volume, respectively (Havaej et al., 2016).

In this study, we use a two-dimensional finite element code to investigate the rock mass stability around the Monte Seco tunnel, located in Minas Gerais, Brazil. (Figure 1) illustrates the methodology adopted. TLS is performed at the site in order to characterize the rock mass. The point cloud derived from the TLS is used to reproduce a realistic rock mass geometry for a 10-m length representative section of the tunnel which is then *incorporated into the numerical simulations using finite elements. Discontinuity mapping is also performed using the TLS data, which allows developing realistic DFNs. TLS data is also used to reproduce overbreak profiles of tunnel sections which are then compared with two-dimensional numerical simulation results.*

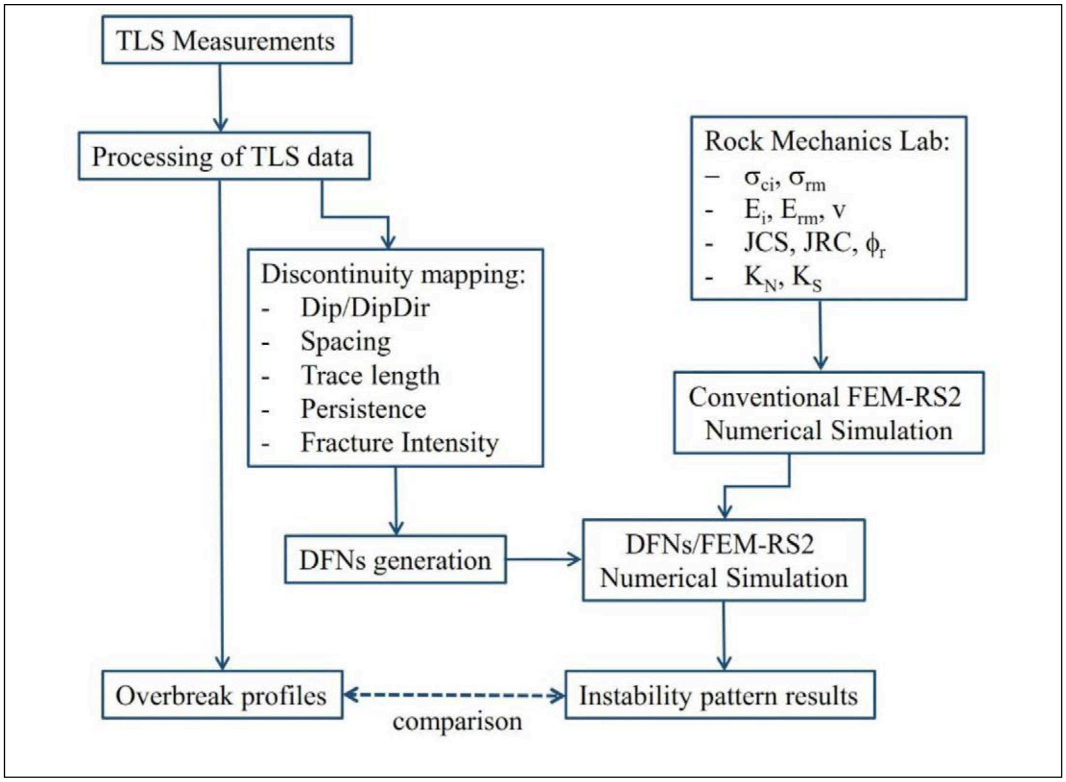

Figure 1. *Methodology adopted for rock mass characterization and subsequent numerical simulations*

3. Case study: Monte Seco Tunnel

In Brazil, there are several old tunnels of the highway and railroad system that date from the 1950s. They were built in rock masses with a very good geotechnical quality but without any reinforcement or support system. Today, some of these tunnels have seen localized problems with the formation and falls of rock blocks, mainly associated to the distribution of discontinuity systems and one-off degradation processes of the associated geomechanical parameters.

The Monte Seco Tunnel is an old linear underground project built for the Vitoria-Minas railroad in the State of Espirito Santo in the southeast of Brazil see (Figure 2). It belongs to the mining company, VALE S.A. This tunnel has required a series of geological and geotechnical investigations to provide geomechanical parameters and its stability assessments.

Considering this problem, a joint project was started between the Polytechnic School of the Universidade de São Paulo and the Mining Company, VALE S.A., to propose a study methodology of the tunnel's current state. Thus, the Monte Seco tunnel has been transformed into a valuable source of geomechanical information to study the stability of underground projects built in discontinuous rock masses. Below, the main characteristics and properties considered for this work, are presented.

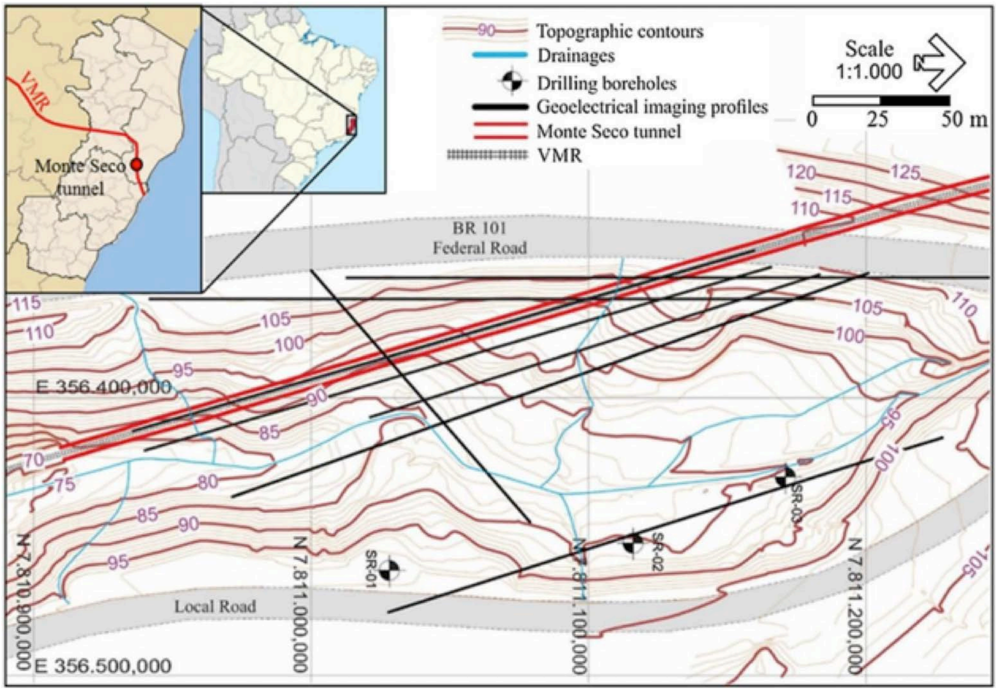

Figure 2. *Location of the Monte Seco tunnel and geotechnical investigations performed at the tunnel site (Cacciari and Futai, 2017)*

3.1 Geo-structural data collection

The Monte Seco tunnel is located in the Province of Mantiqueira, built in a rock mass formed by a Gneiss (metamorphism of sedimentary rock), with mylonitic texture, comprising felsic (with a predominance of quartz and feldspar) and mafic bands (with a predominance of biotite and amphibolite), with pronounced foliation, mainly due to the orientation of mica. In addition, in several portions within the tunnel, as well as in the outcrop of external rocks, pockets of Granite inserted in the Gneiss were seen with diameters of between 1.0 and 3.0-m, with abrupt contacts, without foliation and with a pegmatitic texture.

(Cacciari and Futai, 2017) have geotechnically characterized the discontinuity systems using the remote techniques known as TLS to generate the point clouds shown in (Figure 3a). The methodology used can be summarized in the following three steps: (i) complete mapping of discontinuities in the TLS point clouds, measuring all the positions, trace lengths and orientations of each set of discontinuities; (ii) discontinuity analysis to determine the probability density functions of the diameters and orientations of each set of discontinuities; and (iii) calculation of the volumetric intensity parameters, P_{32} *and* P_{21} *for each set of discontinuities.*

The mapping of the discontinuity systems in the TLS points cloud basically consists in the interpretation of the discontinuities present in the tunnel's rock surface (i.e., walls and roof) and make their respective measurements. The orientation is measured through the selection of coplanar points to the exposed areas of the discontinuities and extracting the normal vector to the adjusted plane for these points. Below, the normal vectors measured are converted to the geo-structural notation (i.e., Dip and DipDir). The traces are the intersection between the discontinuities and the exposed rock surface within the tunnel. Finally, the trace lengths are measured taking the distance between the final points of the adjusted polylines in these traces. (Figures 3b) and (Figure 3c) show examples of the trace length measurements and orientation in the points cloud.

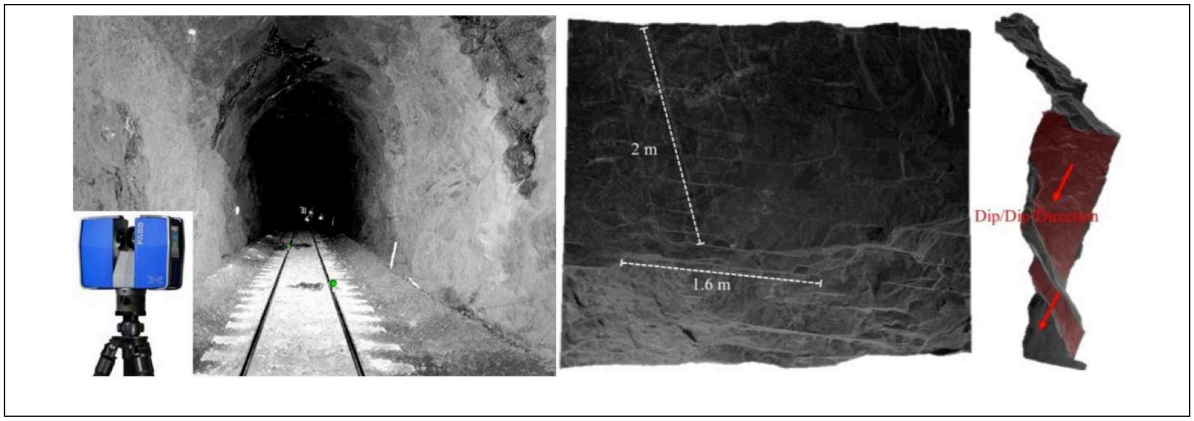

Figure 3. *a) Faro Focus 3D laser scanner model and an example of the Monte Seco Tunnel's TLS image (point cloud) generated by this instrument, b) measurement of trace lengths and c) measurement of orientation*

3.2 Geo-structural data analysis

The Monte Seco Tunnel was built in a Gneiss rock mass, where four discontinuity systems were identified and characterized during the in-situ inspection. Two fracture systems along cut F1 and F2, a laminar jointing system F3, and a foliation system Sn. These discontinuity systems were mapped in detail with the TLS images. (Figure 4a) shows the orientation measurements in the TLS images with the identification of each one of these discontinuity systems and the tunnel direction. (Figure 4b) preliminarily shows the formation and instability of the blocks which tend to slide and fall inside the tunnel excavation.

In most cases found in technical literature, trace lengths are described using log-normal, gamma or exponential distributions (McMahon, 1974); (Call et al., 1976); (Baecher et al., 1977); (Priest and Hudson, 1981); (Kulatilake and Wu, 1984); (Villaescusa and Brown, 1992); (Zhang and Einstein, 2000). All the trace lengths of the F1, F2 and F3 systems mapped in the tunnel's TLS images were analyzed by statistical tests to find the distribution form that they best fit. (Figure 5) shows the distribution that best fits for each discontinuity system, with this being log-normal distribution in all cases. The foliation system is considered as persistent in the tunnel's scale; therefore, its traces were not statistically analyzed. Particularly for the 10-m long tunnel section evaluated, the F3 system was not found. The geo-structural data considered for the numerical simulations are summarized in (Table 1).

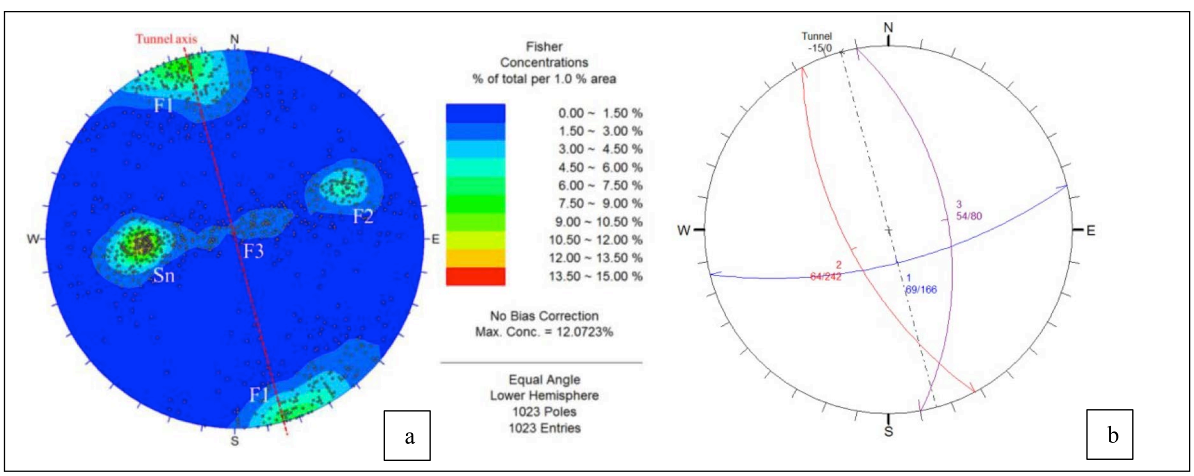

Figure 4. Stereographic plot of the discontinuity orientation measured in TLS images: (a) pole concentrations, (b) representative planes without F3 system

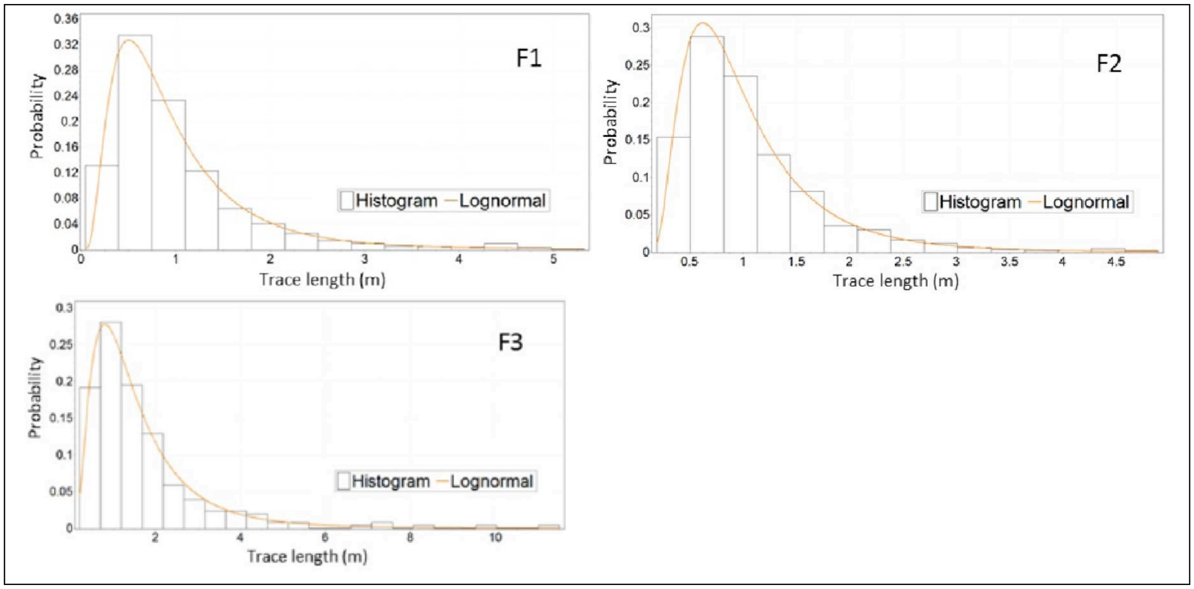

Figure 5. Log-normal distributions fitted to F1, F2 and F3 trace length data

3.3 Intact rock and discontinuity parameters

Following the recommendations indicated by the International Society for Rock Mechanics (Bieniawski and Bernede, 1979); (Ulusay, 2015), uniaxial compression tests were made considering three different orientations of the foliation system. In addition, the measurement of the axial and radial deformations has been made using strain gauges installed on the test specimens. With this, the resistance to the uniaxial compression and the elastic parameters were obtained, i.e. the elasticity modulus and Poisson coefficient of the intact rock (Ito, 2016). These parameters have been used in the numerical simulations.

(Table 2) presents a summary of the results obtained for the uniaxial compression tests. From the results, a substantial reduction in the resistance was seen, close to 50%, mainly in the test specimens which have altered minerals and cracks.

In addition, a series of different tests, such as direct and indirect traction, tilt test and sclerometer have been made to determine the geomechanical parameters of the discontinuity systems (Barrios, 2014); (Ito, 2016); (Monticelli, 2014). For the three discontinuity systems (F1, F2 and Sn), the Barton-Bandis failure criteria has been considered (Bandis et al., 1981); (Barton et al., 1985). (Table 3) presents a summary of the corresponding shear strength parameters for each discontinuity system.

The normal and shear stiffness of discontinuity systems were estimated from rock mass modulus, intact rock modulus and joint spacing. It is assumed that the deformability of a rock mass is due to the deformability of the intact rock and the deformability of the discontinuities in the rock mass, with K_N *= 3.5 GPa/m for F1 and F2, and* K_N *= 2.8 GPa/m for Sn. In this paper, the shear stiffness of the discontinuities was estimated using the ratio* K_N/K_S *= 10.*

A very important and influential aspect within this work is the degradation the different discontinuity planes have experienced as time has gone by. (Monticelli, 2014) made the characterization of the alteration processes of the Monte Seco Tunnel's rock mass, concluding that the type of weathering is a moderate to strong intensity chemical type, presenting a strong structural control related to the presence of fractures and foliation. The foliation intensifies the alteration process of the rock matrix of the blocks formed around the tunnel, facilitating the percolation of water through the inter and trans mineral fissures formed in the altered planes. Both in the rock matrix and in the discontinuity planes, the different degrees of alteration have a micro-morphological nature (fissures and pores) related to expansion-contraction processes of the secondary mineralogy comprising Pyrite, Chlorite and Smectite aggregates, the latter confirmed in the X-ray diffractometry tests, where it was also seen that the fracture planes have alteration processes controlled by the inter-mineral fissures connected throughout the foliation, and that the trans-mineral fissures are quite expressive and parallel to the fracture planes occurring with and without Iron Chlorite Oxide fills.

Table 1. Geo-structural data used for two-dimensional DFNs generation

Discontinuity System	**F1**	**F2**	**Sn**
Dip (°)	69	64	54
DipDir (°)	166	242	80
K (Fisher)	32.8	251.3	78.9
Std. Dev. (°)	15.2	5.5	9.8
Spacing (m)	0.48	0.32	0.5
Trace Length (m)	3.67	3.91	Infinite
Persistence	0.5	0.75	-
P_{21} (m/m^2)	0.48	2.51	-

Table 2. Intact rock strength and elastic parameters

Parameter	**Σ (MPa)**	**E_i (GPa)**	***v*** **(-)**
Range	121 – 159	51 – 67	0.18 – 0.35
Mean	139	65	0.25
Std. Dev.	19	14.5	0.11

Table 3. Barton-Bandis joint strength parameters

Parameter	***JCS*** **(MPa)**		***JRC*** **(-)**		**φ (°)**	
	F1 - F2	Sn	F1 - F2	Sn	F1 - F2	Sn
Range	80 – 140	120 – 140	9 – 13	8 – 10.5	23 – 29	24 – 30
Media	110.4	126.3	10.5	8.8	25.6	27.9
Std.Dev.	30.6	11.6	2.1	1.4	3.1	3.5

4. FEM numerical modelling

Based on the geological and rock mechanics information described above, plane-strain semi- discontinuous elasto-plastic numerical models were completed using a commercial software.

4.1 Boundary conditions and in-situ stresses

Because the main objective of this work was to observe the rock mass stability behavior around the tunnel excavation, the edges of the finite elements model have been restricted to the horizontal and vertical directions. Triangular finite elements with three nodes were used in the analysis, considering a higher density finite elements mesh near the excavation see (Figure 6a). The tunnel shape is defined as a 6.5-m high and 6.0-m wide horseshoe see (Figure 6b). The in-situ vertical stress state was estimated considering the lithology column on the tunnel's roof, and with a horizontal/vertical stress ratio K0 = 1,35. The shallow tunnel is located at a depth ranging from 35-m to 45-m. A vertical stress of 1.0 MPa was applied to the model to simulate the gravitational loading of the overburden rock mass strata. This is based on an average overburden depth of 40-m and an overburden material density of 25 kN/m^3.

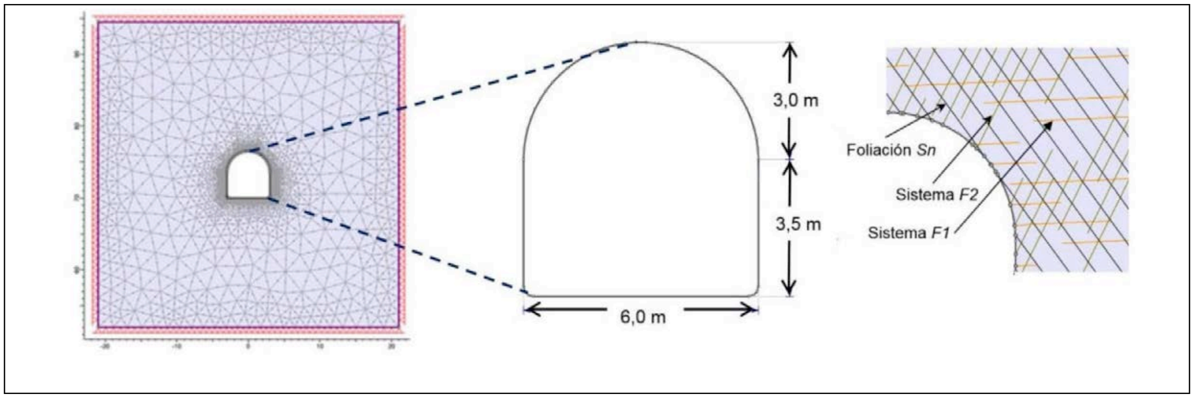

Figure 6. (a) Geometry and boundary conditions of finite elements model, (b) dimensions of horseshoe tunnel section, and (c) random rock joint system generation (Villalobos et al. 2017)

4.2 Rock mass model

The rock mass material model selected was the generalized Hoek-Brown (Hoek et al., 2002). It has been adapted in accordance with the methodology described in (Diederichs, 2007), whereby peak and residual strength parameters are selected so that strain-softening behavior occurs close to the excavation perimeter whilst under increasing confinement (i.e., further from the excavation perimeter, strain-hardening occurs). Three clearly defined rock discontinuity systems (fracture planes: F1, F2; and foliation plane: Sn) were considered to follow the Barton-Bandis failure criteria (Bandis et al., 1981); (Barton et al., 1985).

4.3 Generation of rock discontinuity systems

The numerical modelling has incorporated the geo-structural data to evaluate the formation and stability of rock blocks around the tunnel excavation. The rock mass was modelled as elastic-plastic material type intersected by geological discontinuities, in this case the network of rock discontinuity systems presented in (Table 1). Considering the mechanical properties of intact rock and discontinuities, one can predict major failures controlled by discontinuities in the semi-discontinuous model. It was considered as an intact rock material with good mechanical properties, as a result the discontinuities are generally much weaker mechanical properties than the intact rock blocks. Therefore, the semi-discontinuous numerical modelling provides a valuable analysis tool because the displacement of unstable blocks along rock discontinuity systems is allowed. For the semi-discontinuous numerical modeling, which explicitly considered the rock mass' discontinuity systems, three discontinuity mesh generation methodologies have been evaluated. These are described below.

4.3.1 Parallel deterministic model

The parallel deterministic model was developed for rock discontinuities that define a network of parallel discontinuities with a fixed spacing and orientation. In this case, deterministic refers to the fact that the spacing, length and persistence of the joints is assumed to be constant (i.e., known precisely with no statistical variation). However, the parallel deterministic model does allow randomness of the joint location. The orientation defined by the trace plane in the discontinuity network is simply the cross-sectional plane of the model. The spacing is the perpendicular distance between the parallel discontinuity planes. For the parallel deterministic model, the spacing is a constant value.

4.3.2 Parallel Statistical Model

The parallel statistical model allows defining a network of parallel discontinuities with defined statistical distributions, log-normal in this case, for the spacing, length and persistence of discontinuities. The orientation parameters for the parallel statistical discontinuity network model have the same definition as the parallel deterministic model. The spacing, trace length and persistence can be defined as a random variable by selecting a statistical distribution, and entering the mean, standard deviation and relative minimum and maximum values. For the parallel statistical model, if both the trace length and persistence are defined as random variables, then the length of each discontinuity segment, and the gap of intact material between adjacent discontinuity segments, will be variable, according to the statistical distributions defined.

4.3.3 Baecher model

The major feature of the Baecher model is the assumption of circular discontinuity shape. The following geometric parameters are required to generate the discrete discontinuity network: density of the discontinuities (number of discontinuities per unit area), the orientation distribution of these discontinuities, the size and shape of the discontinuities. Discontinuity centers are located uniformly in space, using a Poisson process and the discontinuities are generated as discs with a given radius and orientation. As a result of the fracture location, shape and size process of the model, discontinuities terminate in intact rock and intersect each other. Any combination of discontinuity size, location and orientation assumptions is possible (Grenon et al., 2017).

5. Outcomes and Evaluation

An explicit network of rock discontinuity systems was generated within a limited area to reduce computation time while maintaining a high accuracy in the immediate vicinity of the tunnel excavation. The generation of rock discontinuity systems was used to provide more realistic representations of the jointing patterns based on the geo-structural data.

Below, the results of the two-dimensional analysis are presented, explicitly considering the geo-structural data. It is important to indicate that this sensitivity analysis has the purpose of evaluating, in a simple manner, the stability of the rock mass around the tunnel. From this data, it is possible to verify the failure patterns defined by the intersection of two or more discontinuity systems, and the influence of the geo-structural data on the numerical model.

5.1 Displacements and failure patterns

The variation of the displacement boundary and the extension of the shear zone on the tunnel's perimeter for the three methods used to generate the two-dimensional discontinuity networks, is shown in (Figure 7). In this work, the analysis focus considers the shear of the discontinuity systems, which induce the formation and instability of rock blocks around the excavation.

The zone disturbed around the tunnel is the region where the original state of in situ stresses has been affected due to the excavation works. This is the zone where normally the rock blocks have important displacements and the tangential stresse have the highest increase. In this way, the displacements and stresses are the factors which control the tunnel's stability. In the studied case, the stress field in situ induces the concentration of stresses mainly in the tunnel walls.

The results obtained with the deterministic parallel and statistical parallel methods (Figures 7a) and (Figure 7c) have total displacements of between 3 to 5 mm, giving a good representation of the displacement pattern and failure experimented locally on the tunnel's West wall, i.e., block sizes close to 1.35-m; however, there was not a good fit with what was seen on the East wall. The results of the Baecher model, shown in (Figure 7e) and (Figure 7f), having maximum displacements of the tunnel area of between 3 to 4 mm, indicating greater shear zones with average lengths of close to 0.75-m, both on the East and West walls of the tunnel. This model provides results that are closer to what has been seen and measured in situ, as it assumes much more realistic spatial distribution of discontinuity planes, using the Poisson process. It is worth stating that the formation of unstable blocks in the tunnel's outline is very sensitive to the geometric parameters of the discontinuities (orientation, spacing and persistence), as well as the shear resistance parameters and their stiffness.

5.2 Overbreak measurements

The results obtained with the Baecher model, with a shear zone length of between 0.5 to 1.0-m, are similar to the onsite observations. For this scenario, block slippage is seen with maximum apexes that are equal to 1.0-m on the East wall right wall in all (Figure 7) and (Figure 8), which fits very well with the over excavation measurements made using TLS in the tunnel. These results are similar to that seen in the tunnel's overexcavation profiles, which *were measured with TLS. The overexcavation measurements made, show that the type of failure that commonly occurred inside the tunnel, has been block falls with apexes below 1.5-m on the East wall, while failure mechanisms have also been seen on the West wall with apexes between 0.85 to 1.25-m.*

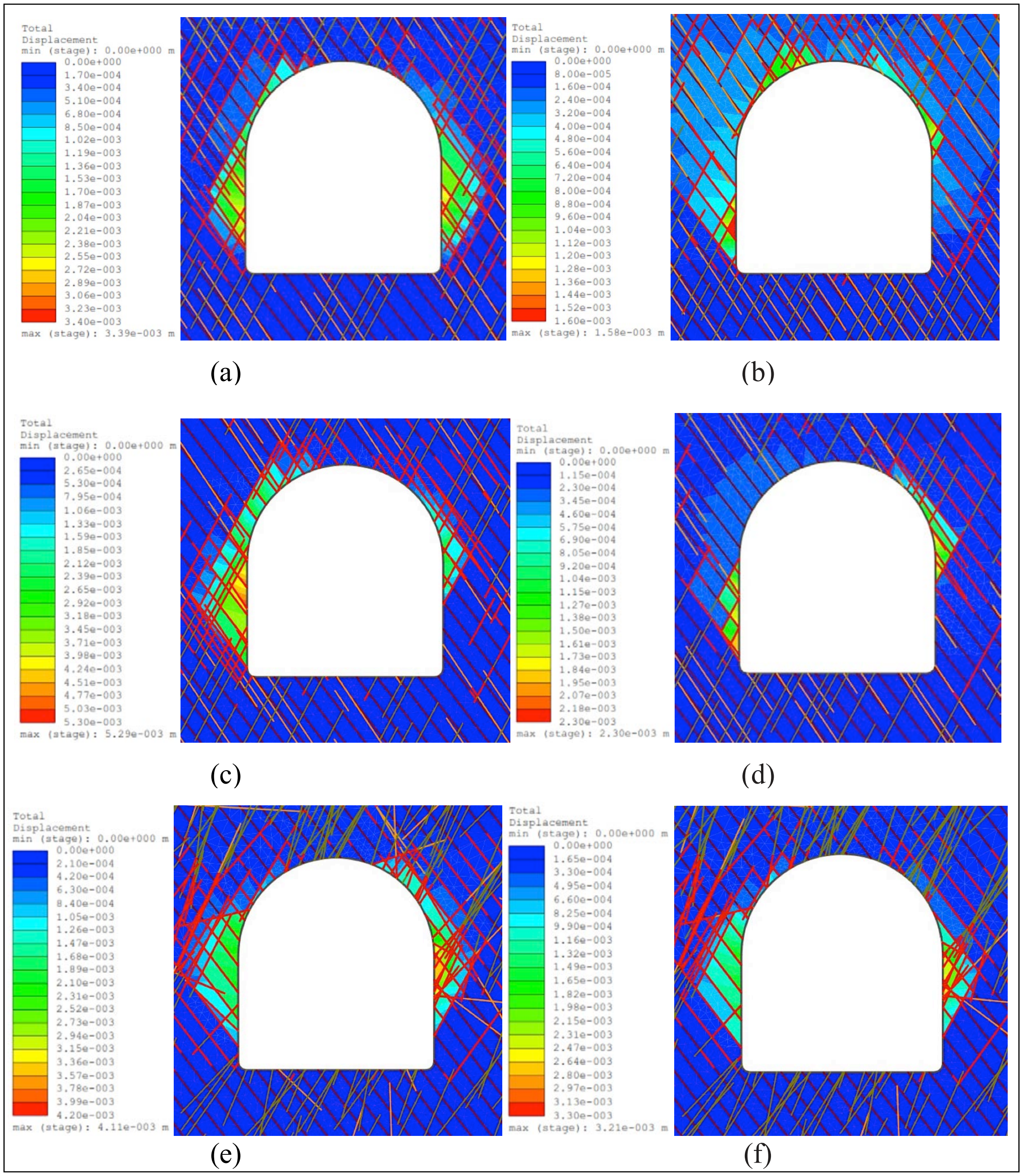

Figure 7. *Displacement contours and yielded zone for different rock discontinuity generation methods: (a) and (b) Parallel deterministic, (c) and (d) Parallel statistical, (e) and (f) Baecher model*

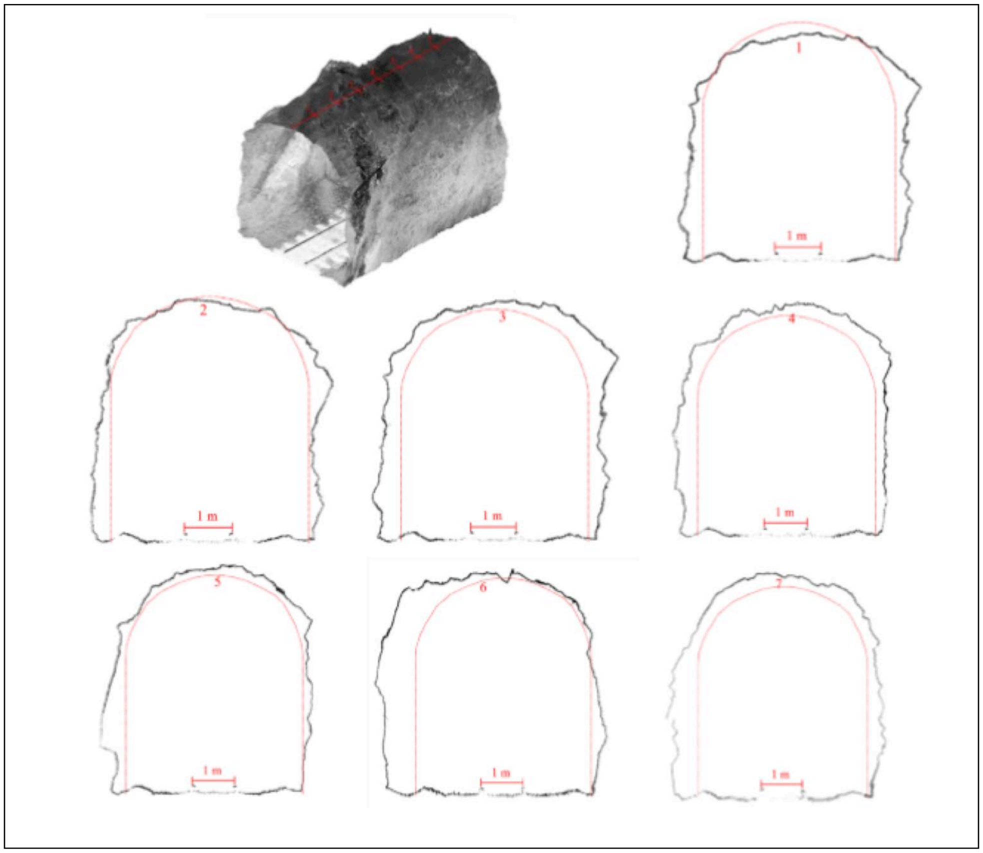

Figure 8. *Overbreak profiles measured using TLS data*

6. Conclusions

In this study, statistical characterization of rock discontinuity systems and a two-dimensional finite element analysis commercial software was used to demonstrate and highlight the importance of explicit modelling rock discontinuity systems on the displacements and stability patterns around tunnels excavated in discontinuous rock masses. With the proposed methodology, using TLS data and numerical simulation through finite elements, the formation and instability of rock blocks around a tunnel excavated in discontinuity rock mass could be evaluated simply and quickly.

Due to the existence of rock discontinuity systems, a plastic zone is formed around the excavation. Some discontinuity plastic zones also appear far away from the tunnel but they have little influence on the stability of the excavation. The results from semi-discontinuous numerical models show an anisotropic behavior on the displacement patterns.

The terrestrial laser scanner technique is a practical and powerful tool for discontinuity mapping in tunnels because it overcomes difficulties associated with the traditional hand-made geological mapping.

The results of the deterministic parallel and statistical parallel models do not show a good fit with the over-excavation profiles of the tunnel's outline measured via TLS. This is because the two-dimensional generation of the DFNs systems using these models, does not consider the facture's intensity parameter.

The results of the Baecher model, where shear zones were obtained, both for the discontinuity systems and the rock mass of between 0.75 to 1.50-m around the tunnel, showed a good fit with the over excavation profiles of the tunnel's outline measured using TLS. This is because this model considers the fracture intensity parameter for the P21 area, which is derived from the fracture intensity parameter by volume P32. Therefore, it makes the systems generated from two-dimensional DFNs more realistic.

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