Study of an old railway rock tunnel: site investigation, laboratory tests, weathering effects and computational analysis.

Etude d'un ancien tunnel rocheux de chemins de fer: étude de site, essais en laboratoire, effets des intempéries et analyse computationnelle.

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ABSTRACT: Several old tunnels along Brazilian railways were constructed in jointed rock masses with no concrete liners or both liners and bolts. In the past few years, some of these tunnels have shown localized stability problems (with sporadic block falls), which demand a reevaluation of the rock mass quality at certain critical areas. The Vitória-Minas railway in Espirito Santo State (southeastern Brazil) has 22 tunnels in this condition, and the intense rail traffic (cargo and passengers) reduces the timeframes available for inspections (geological mapping and geomechanical evaluations). Therefore, an automatic discontinuity analysis method was developed in this project, based on window-samplings and discrete fracture network modeling, applied on 3D terrestrial laser scanner discontinuity mapping. Moreover, laboratory and field tests were performed to characterize the discontinuity and intact rock strengths in different weathering conditions. The results obtained from discontinuity mapping and laboratory tests were used to perform stability analyses.

RÉSUMÉ: Plusieurs vieux tunnels, le long des chemins de fer brésiliens, ont été construits dans des massifs rocheux joints sans doublures de béton ou à la fois des doublures et des boulons. Au cours des dernières années, certains de ces tunnels ont montré des problèmes de stabilité localisés (avec des chutes sporadiques de blocs), qui exigent une réévaluation de la qualité des masses rocheuses dans certaines zones critiques. Le chemin de fer Vitória-Minas dans l'État d'Espirito Santo (sud-est du Brésil) comporte 22 tunnels dans cette condition et le trafic ferroviaire intensif (cargo et passagers) réduit les délais d'inspection (cartographie géologique et évaluations géomécaniques). Par conséquent, une méthode d'analyse de discontinuité automatique a été développée dans ce projet, basée sur des échantillonnages de fenêtre et une modélisation de réseau de fracture discrète, appliquée sur la cartographie de discontinuité de balayage laser terrestre 3D. De plus, des essais en laboratoire et sur le terrain ont été réalisés pour caractériser la discontinuité et les forces de roche intactes dans différentes conditions d'altération. Les résultats obtenus par cartographie de discontinuité et tests de laboratoire ont été utilisés pour effectuer des analyses de stabilité.

KEYWORDS: Tunnel; Discrete Fracture Network, Terrestrial Laser Scanner, Rock Mass, Discontinuities

1 INTRODUCTION

Several old tunnels along Brazilian railways were constructed in jointed rock masses with no concrete liners or both liners and bolts. In the past few years, some of these tunnels have shown localized stability problems (with sporadic block falls), which demand a reevaluation of the rock mass quality at certain critical areas. The Vitória-Minas railway in Espirito Santo State (southeastern Brazil) has 22 tunnels in this condition, and the intense rail traffic (cargo and passengers) reduces the timeframes available for inspections (geological mapping and geomechanical evaluations). Therefore, a partnership was established between the research group GeoinfraUSP (University of São Paulo) and the mining company Vale SA to develop a reliable methodology to assess the stability state of these tunnels (the TUNELCON project).

In tunnels with exposed rock faces, it is advantageous to evaluate the discontinuity intensities continuously, highlighting the most fractured zones of the rock mass and making it easier to define sections (positions with different sizes) of the tunnel to be evaluated in stability analyses. This paper presents the application of 3D terrestrial laser scanner (TLS) for discontinuity mapping and discrete fracture network (DFN) modeling along a tunnel. laboratory and field tests were performed to characterize the discontinuity and intact rock strengths in different weathering conditions. The results obtained from discontinuity mapping and laboratory tests were used to perform stability analyses using the 3D distinct element method (3DEC).

2 TERRESTRIAL LASER SCANNING IN TUNNELS

The Faro Focus laser scanner (www.faro.com) was used to obtain the 3D images and perform discontinuity mapping along the tunnel. Several authors (i.e. Kemeny et al. 2006; Sturzenegger and Stead 2009; Lato et al. 2010; etc.) have used terrestrial remote sensing (TRS) techniques to perform discontinuity mapping of rock outcrops (point clouds or digital models), because of the limitations and difficulties associated with hand-made geological mapping. The TLS is one of the TRS techniques often used in tunnels (Fekete and Diederichs 2010; Cacciari and Futai 2016a) to increase volume and areal extent of orientation and trace length measurements, thereby facilitating the use of sophisticated discontinuity analyses.

Despite the advantages that have been demonstrated in the past few years, TLS, sophisticated discontinuity analyses and DFN are rarely used in engineering practice to create discontinuous rock mass models and perform stability analysis. In case which TLS is used and a detailed discontinuity mapping is available, an automatic, practical and fast discontinuity analysis methodology is necessary to deal with the large amounts of data available Cacciari and Futai 2016b). The methodology presented herein was developed by Cacciari and Futai (2016b and 2016c), composed by three main steps:

1) Full discontinuity mapping of the TLS point clouds measuring all discontinuity positions, trace lengths, and orientations.

2) Automatic discontinuity analysis for determining the probability density functions (pdf) of the diameters and orientations of each discontinuity set.
3) Automatic DFN modeling and 3DEC block model generation using the results obtained in (2).

Some details and examples of this methodology are presented below, using the analyses performed on the Monte Seco tunnel (Vitória-Minas railroad), located in the Espírito Santo State, southeastern Brazil. This tunnel is 1000 m long, without support system, was constructed in a gneiss rock mass.

2 .1 *Discontinuity mapping*

The discontinuity mapping in TLS point cloud consists basically in identifying the discontinuities apparent in the tunnel rock face and taking measurements. The orientation is measured by extracting the normal vector of a plane fitted in the coplanar points of the discontinuity exposed areas. The normal vectors are converted into Dip/Dip direction. Discontinuity trace lengths are measured by taking the distance between the endpoints of polylines fitted in discontinuity traces (intersection between discontinuities and the rock face). Figure 1a shows examples of trace lengths and orientation measurements in the point cloud. The first 325 m of the tunnel were completely mapped via TLS. Four discontinuity sets were identified during field inspections (rock foliation Sn; shear fractures F1 and F2 and sheet joints F3) and the same sets were mapped on the point clouds. Figure 1b and 1c shows the stereonet and trace length distributions obtained by TLS mapping.

2 .2 *DFN-3DEC modeling*

The discontinuity analyses of orientation and trace length data were automated in Visual Basic and Excel. Unbiased mean trace lengths and discontinuity diameters were assessed using sampling windows, following the methodologies proposed by Kulatilake and Wu 1984, Zhang and Einstein 2000 and Wu et al. 2011. The same sequence of methods was applied and validated for tunnels by Cacciari and Futai 2016a, 2016b and 2016c. The automatic methodology for discontinuity analysis consists in selecting a tunnel section and finding the probability density functions of discontinuity diameters and orientations for each set mapped in this section.

DFNs are stochastic models of discontinuity distributions in the rock mass. In 3DEC, discontinuities are considered disc-shaped planes, Poisson distributed in space, with an intensity parameter (i. e. volumetric intensity P32) used as the program termination criteria for discontinuity generation. The size and orientation are characterized by probability density functions obtained by discontinuity analyses. After the DFNs of each discontinuity set are created, the discontinuity intersections are automatically used in 3DEC to create de block models. The DFN and 3DEC codes were written in FISH (www.itascacg.com) to automatically read the discontinuity analyses results (input data tables) and create the block models. Figure 2 exemplifies this process for a 10 m long section of the tunnel. The block models created (such as in Figure 2c) are used for stability analysis.

2 .2 *Roughness characterization*

TLS was also used for obtaining roughness profiles of discontinuity planes along the tunnel (Cantarella et al, 2016). The profiles are taken from discontinuity planes selected on the tunnel point cloud (Figure 3a). The maximum amplitude is analyzed by fitting a flat mean plane to the selected points and checking the orthogonal distances between features (Figure 3b). Next, the chart proposed by Barton (2013) is used to find the respective JRC for each amplitude measured, and average values are taken for each discontinuity set (Figure 3c). Additionally, the standard profiles method was also used in the tunnel rock face during field inspections for comparison.

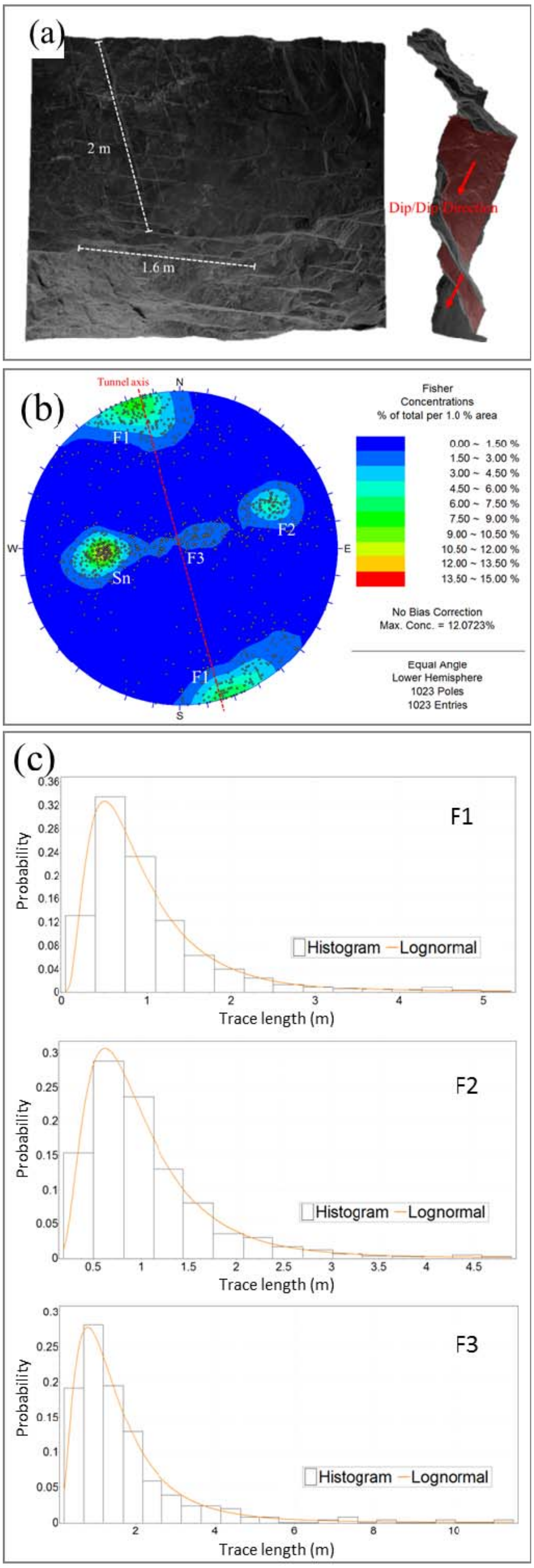

Figure 1. (a) Example of discontinuity measurements in TLS point clouds. (b) Stereonet with the measured orientation data. (c) probability distributions of discontinuity traces (Cacciari and Futai 2016c).

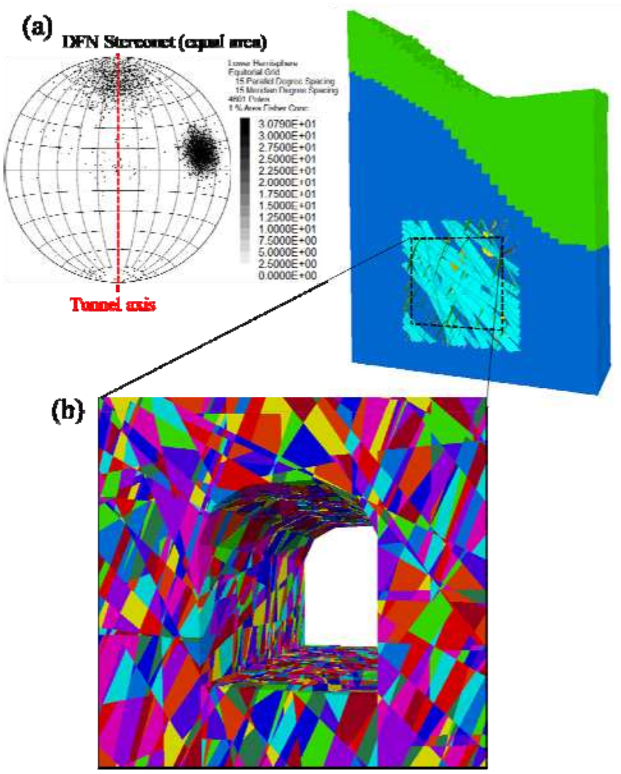

Figure 2. (a) Model of a 10-m-long section of the Monte Seco tunnel, indicating the DFNs generated. (b) Block model created after discontinuity intersections (Cacciari and Futai 2016c). .

3 LABORATORY AND IN SITU TESTS

3.1 *Schmidt hammer for Joint Strength coefficient determination*

The Schmidt hummer was used to obtain the rebound number of F1, F2, F3 and Sn along the tunnel, with more than 10 estimates for each discontinuity set. The Joint compressive strength (JCS) was calculated by the empirical relation proposed by Aydin and Basu (2005):

$$JCS = 1.44e^{0.07R} \tag{1}$$

Where R are the rebound numbers number obtained from the weathered and rough joint surfaces (in situ). Table 1 summarizes the mean R and JCS results from each joint set. The mean uniaxial compressive strength (from more than 10 laboratory tests) is also presented on Table 1 for comparison with the JCS values.

Table 1. R, JCS and UCS measurements.

Set	R	JCS (Mpa)	UCS (Mpa)
F1, F2 and F3	57	81	155
Sn	55.5	73	

3.2 *Weathering grades of rock discontinuities*

The weathering grades of the rock classified using the porosity measurements (%) and Ja classifications (Barton et al. 1974). With these indexes, three different weathering grades were suggested with respective residual friction angle estimates (Monticeli et al. 2016). These results are presented in Table 2.

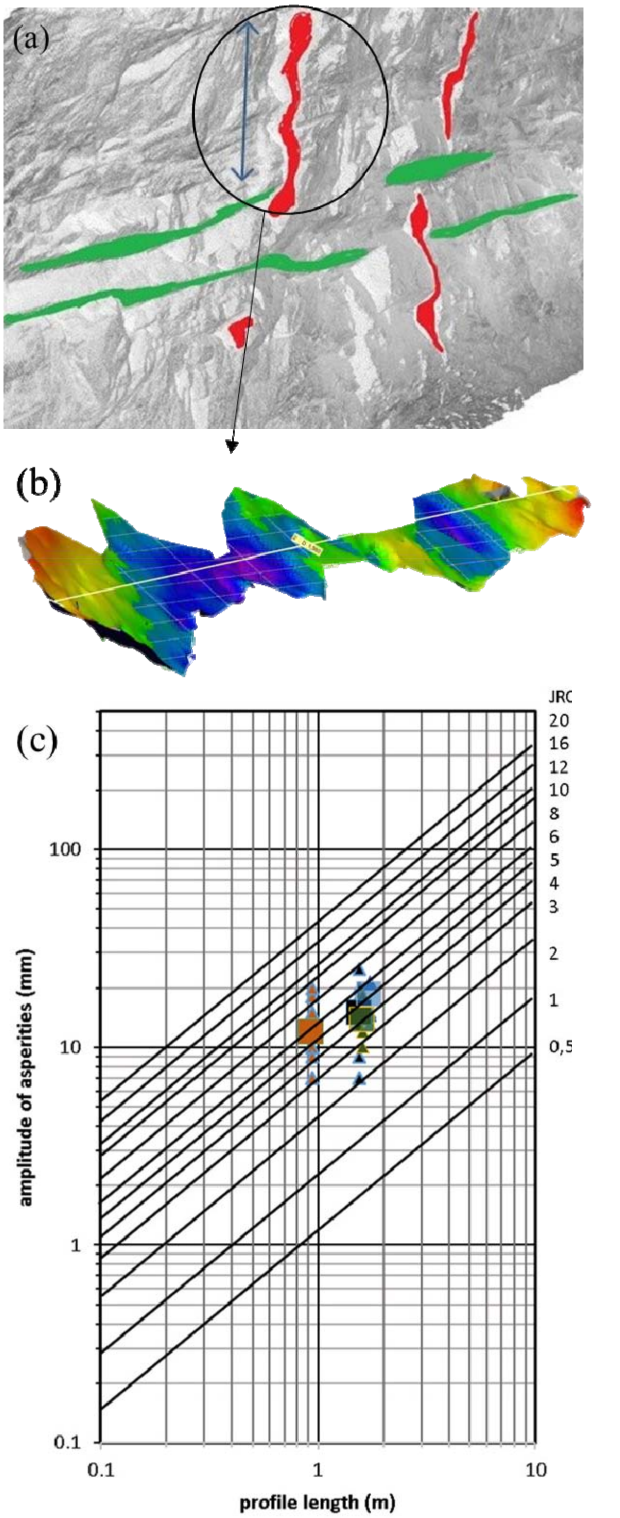

Figure 3. (a) Example of discontinuity planes selected for roughness measurements in TLS point clouds. (b) Example of roughness amplitude measurement. (c) Chart with the amplitude plots and respective JRC values (Cantarella et al, 2016).

4 NUMERICAL ANALYSIS

The numerical analysis are performed with 3DEC block models. The mechanical parameters obtained by laboratory and in situ tests (JRC, JCS, Ja and Φr) are used as input to the Barton-Bandis criterion (Bandis et al. 1981). However, equivalent cohesionless Mohr-Coulomb envelopes were estimated for each joint set using the Barton-Bandis envelopes obtained, as 3DEC does not support the Barton-Bandis model. The rock blocks are considered rigid; thus, the mechanical parameters of intact rock are not required, and only the rock density (i. e. 27 kN/m^3) is used. Figure 4a show an example of numerical analysis indicating the block displacements around the excavation surface. Figure 3b shows some typical cross sections of the tunnel (from TLS point clouds), indicating the similarity between simulated and real failure patterns.

Table 2. Weathering grades classified for the different discontinuity sets in the tunnel site (Monticeli et al. 2016).

Weatherig grade	Specimen	Pa (%)	Ja	Φr (°)
W1	W1S1	0.61	1	25-25
	W1S2	0.77	0.75	-
	W1S3	0.8	-	-
W2	W2S1	1.01	1 to 2	25-35
	W2S2	1.73	2 to 3	20-25
	W2S3	2.8	2 to 3	20-25
W3	W3S1	5.15	3 to 4	8 to 16
	W3S2	6.35	-	-
	W3S3	6.87	-	-

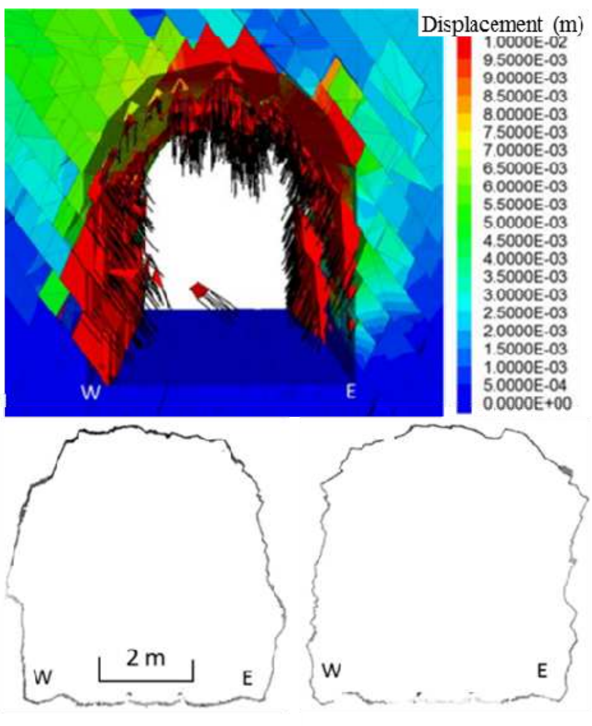

Figure 4. (a) Example of numerical analysis indicating the block displacements around the excavation. (b) Typical cross sections of the Monte Seco tunnel obtained by the TLS point cloud (Cacciari and Futai 2016c).

5 CONCLUSIONS

A methodology integrating terrestrial laser scanning and discrete fracture networks was presented for tunnel modelling in fractured rock masses. The 3DEC software was used to generate DFNs and the block model of 10 m long section of the Monte Seco tunnel. The mechanical parameters and weathering grades of rock discontinuities were estimated by TLS images, Schmidt hummer in situ tests, porosity measurements and visual descriptions. Several other researches are undergoing, including laboratory tests (Brazilian disc test, direct shear test, uniaxial compression tests, etc.) using specimens of the gneiss in different weathering conditions. Moreover, reliability analyses are also being performed using continuous and discontinuous numerical models.

All the methods and results presented herein can be used for different purposes, such as deterministic or probabilistic stability analysis, reliability analyses, investigate the influence of weathering on the tunnel stability, support requirements and design, among others; thus, they is promising and important for rock mechanics and tunneling.

3 ACKNOWLEDGEMENTS

The authors would like to thank the company VALE SA, FAPESP and the Brazilian National Council of Scientific and Technological Development (CNPq) for the logistical and financial support.

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