The accurate knowledge of the joint term for rock mass classification and for the numerical tunnels analysis and its impact on the on the reinforcement's costs

Wagdi Naime
Universidad Central de Venezuela, Caracas, Venezuela

Roque García Ruiz
Universidad Católica Andrés Bello, Caracas, Venezuela

ABSTRACT: There is an interesting discussion amongst experts about the term discontinuity in the geomechanical rock mass classification for subsurface works applications. This definition, covers the formational planes, like bedding planes and foliation planes, moving fractures and the joints. Using the finite element program, the influence of the rock mass zoning on the stability results and on the dimensions of the required reinforcement were analyzed. The stress relaxation method was considered, defining the characteristic curves for the rock and for the reinforcement. A comparative analysis of the impact on the reinforcement costs is shown when compared with non-zoning model. The proposal is presented to avoid the term discontinuity and to differentiate the real geological structures that affect the rock mass, planes of large continuity, stratification and foliation, from the joints, defined as non-moving fractures whose extension and frequency depend on the changes of the stress state of the rock mass.

Keywords: discontinuity, joint, geomechanical classification, tunnel analysis.

1 INTRODUCTION

According to the International Society for Rock Mechanics and Rock Engineering (ISRM), discontinuity is a general term denoting any separation in a rock mass having zero or low tensile strength. It is the collective term for most types of joints, weak bedding planes, weak schistocity planes, weakness zones, and faults (Brown, 1981). The previous definition involves several terms, covering the formational planes, no displacement fractures or joints, and moving fractures, mostly with different mechanical behaviors. This diversity hinders the correct application of terms in the rock mass engineering classification and also affect the numerical analysis on rock mechanics, this has led to errors in rock mass evaluation worldwide, with significant cost overruns but with a high safety factor (Naime & García, 2022, 2023).

In the rock engineering classification, it's important to separate the formational planes, such as bedding planes and foliation planes, from the joints, which are formed due to mechanical effects. Joints should not be considered as fixed patterns; they are non-moving fractures whose orientation and development depend on the variations of the stress state.

In the evaluation of rock masses for subsurface works, empirical methods only consider constant parameters, not taking into account the variations due to the change of the stress state. Therefore, the current knowledge of joints in the rock mass, considered as fixed patterns, must be updated to variable patterns and differentiated from the rest of the structures associated with the discontinuity term.

2 DECOMPRESSED ZONE, JOINT DEVELOPMENT AND SEISMIC VELOCITIES

In geological terms, joints also known as fractures without movement and of little importance in regional interpretations in applied geology, have acquired great importance in projects such as open pit excavations and tunnels, even though they are viewed as fixed patterns, they are not, according to the results of detailed observations, in outcrops, in cut slopes as well as in tunnel excavations (García & García, 2004; García, 2018; García & García, 2021; Naime & García, 2023).

The joints are visibly exposed as a result of the change in stress as confinement in the rock mass is released. These were not hidden with the same characteristics they now show. Perhaps they did not even exist before the excavation. This occurs during a tunnel excavation, with the so-called decompressed zone, where the intact rock is limited by a greater number of joint planes, which originate from microfractures in the rock mass, which develop when stress is released. The resulting decompressed zone, near the excavation border, is related to the joint patterns larger size and high density, compared to the zones with small stress changes, occurring beyond the decompressed zone. The rock mass is zoned, differentiating between Decompressed Zone (DZ) with a transition zone (TZ) and Non-Decompressed Zone (NDZ), Figure 1. The quantification of the rock mass from seismic velocities describes a direct relationship with the joints.

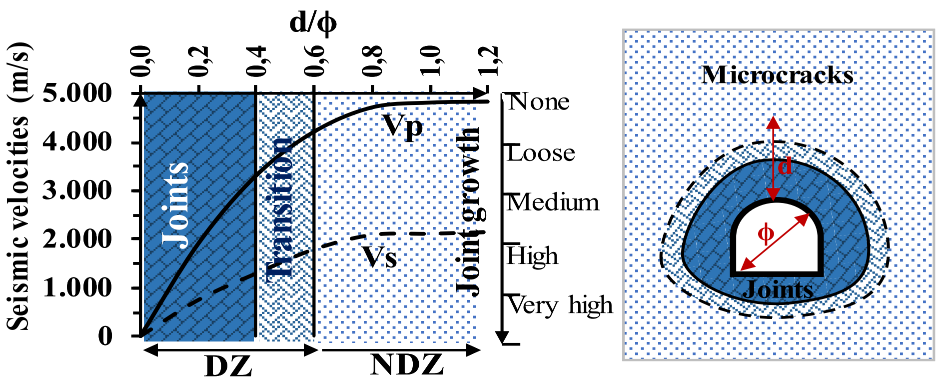

Figure 1. Schematic model defining decompressed zone (DZ) and joints growth during tunnel excavation according to the micro-seismic velocities (Vp, Vs) and the distance from the excavation /tunnel diameter ratio (d/ϕ).

The initial stress state and the size of the tunnel excavation, are factors that determine the variations in stress of the rock mass, and consequently, also determine the formation, density and the extension of the joints. The resulting decompressed zone is related to the joint patterns larger size and high density, compared to the zones with small stress changes, occurring beyond the decompressed zone (Naime & García, 2022, 2023).

The decompressed zone is an example of misusing the terminology regarding geological structures, associated in the term discontinuity, where the properties of the rock mass are related to the development and frequency of the joints from microfractures, due to stress changes. Therefore, rock mass evaluations from observations on excavated or exposed surfaces are representative of a particular stress state and not representative of confined rock masses.

3 ZONED MODEL FOR THE TUNNEL ANALYSIS

A zoned model attempts to represent the variations of the rock mass characteristics with respect to the changes in stress caused by the tunnel.

Generally, a tunnel excavation will develop joints whose density will be reduced with the distance from the excavation. Figure 2 outlines the zoning of the rock mass, to model changes in joint density and strength variation in tunnel analysis, based on stress changes and also according to some well-known elasto-plastic models.

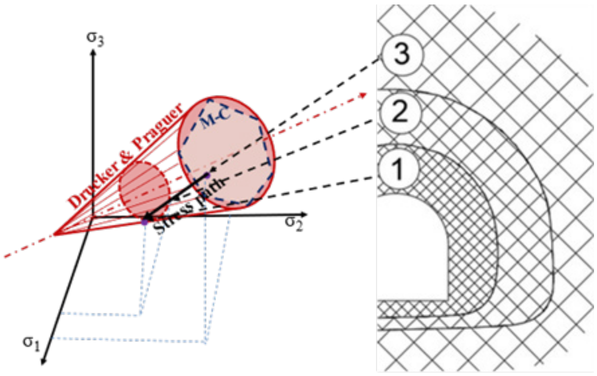

Figure 2. Zoning of the rock mass to model changes in joint density and strength variation in numerical tunnel analysis (Naime & García, 2023).

Thus, as a result of excavating a tunnel section of diameter (φ), there will be variation in the material characteristics according to the distance from the excavation (d) with symmetrical ovals of resistance, which will vary according to the stress path.

It's a common error to consider joints with predefined patterns and uniform characteristics in the rock mass, equal to the directly observed one, which were formed due to the highly modified stress state. This joint pattern is modified because the stress change is reduced as the distance to the excavation increases. There are several signs of joint pattern variations according to the stress states changes, some already discussed in many publications such as García & García (2021), Moore & Lockner (1995), Naime & García (2023) and others. Table 1 presents the measured seismic velocities after construction was completed, in three tunnels in Venezuela.

Table 1. Seismic velocities measured in excavated tunnels.

Tunnel		**DZ Size m**	**V_p**	**V_S**	**NDZ V_p m/s**	**V_S**
	maximum	3,5	2.750	1.330	4.000	2.200
Yacambú (4 m)	minimum	0,3	400	180	1.400	750
	mean	0,9	1.569	699	2.593	1.406
	maximum	4,0	3.000	350	5.500	3.400
Aguaviva (6 m)	minimum	0,5	1.710	670	1580	960
	mean	1,1	1.764	981	3.437	2.057
	maximum	5,5	1.500	1.100	3.200	1.700
Estanques (9 m)	minimum	3,5	860	400	1.600	900
	mean	2,7	1.135	714	2.330	1.226

The size of the decompressed zone was 0.25 to 0.9 times the excavation diameter. Beyond this zone, there are clearly distinguished areas less affected by the stress discharge, which maintained the original seismic velocities. In these three cases, it was observed that the decompressed zone loses between 35% to 70% of the seismic velocity with respect to the unaffected zone.

3.1 *The formational structural planes in tunnel excavation*

The continuous planes as the bedding planes and foliation planes, control the joint patterns that generally remain perpendicular to them, maintaining orthogonal systems. Joint patterns in sedimentary and metamorphic rocks are related to the position of the principal bedding or foliation planes, respectively. Tunnel excavation on stratified rocks generates a bending effect on the layers and orthogonal opened joints. Although blocks are formed, the deformation is controlled by the main planes, as shown by physical models and by numerical models, Figure 3 (García et al. 1998 and Naime & García 2022, 2023)

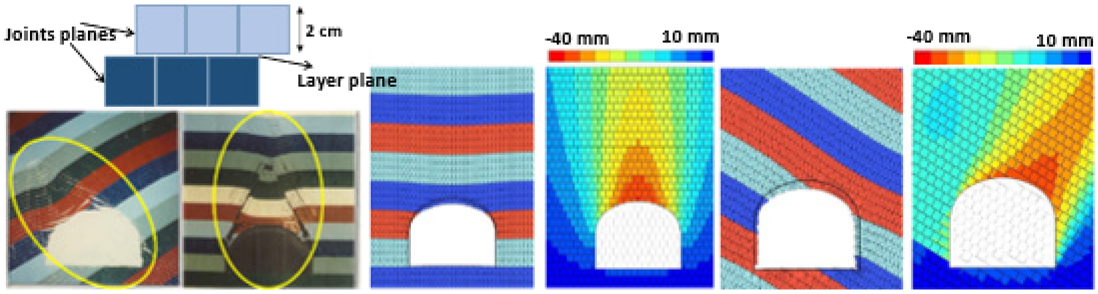

Figure 3. Deformation result in two dimensional physical and numerical models.

The lateral deformations of the layers are limited, generating an oval shape in the deformation zone. The layer thickness/tunnel diameter ratio (D/φ) has a great influence on the deformations. If (D/φ) ≥ 1, the bending effect is minimal, but if (D/φ) is small, then large deformations will occur.

3.2 *Numerical tunnel analysis*

In layered rocks, the number of joints perpendicular to the main planes increases if the distance to the excavation is low. In uniform massifs such as igneous rocks, with low to medium depths of excavation, zoning can be considered concentrically around the tunnel, noting that the rock strength will vary across the rock mass. A joint pattern is formed with high density or high frequency at the edge of the excavation, but due to the confinement at a certain distance, the joint density is significantly reduced. At great depths, the joints will form with sub-horizontal patterns on the tunnel vault and sub-vertical patterns towards the gables. Explosive rocks can appear produced by the sub-horizontal joints, forming layers, which, when subjected to sudden stress changes, will produce abrupt failures.

Using the finite element program (PLAXIS 2D), the influence of the rock mass zoning on the stability results and on the dimensions of the required reinforcement were analyzed. The stress relaxation method was considered, defining the characteristic curves for the rock and for the reinforcement. The reinforcement evaluated was the required thickness of shotcrete, which was determined based on the characteristic curves for the optimum equilibrium condition by the soil-structure interaction condition.

In Figure 4, φ is the equivalent diameter of the tunnel. DZ has characteristics of the decompressed (poor) zone, TZ has characteristics of the transition zone and NDZ has characteristics of the non-decompressed (best) zone. Naime & García (2022, 2023) present several examples of comparative analyses between deformations with zoned models and non-zoned models. In this figure, on the left-hand side, another example is shown, where we illustrate that in the non-zoned model the deformations are widely concentrated towards the vault. On the right, it is shown how the required thickness of reinforcement is modified in relation to the zoning in the numerical model. The curves at the extreme borders are for non-zoned models, The curve above was calculated considering only ZD material and the curve below only NDZ material. The two intermediate curves show zoned models with the thicknesses of the three zones indicated in the figure. In one curve the DZ is formed up to a distance φ and the TZ up to a distance of 1.5 φ, the other curve with respective values of 0.5 φ and 0.75 φ.

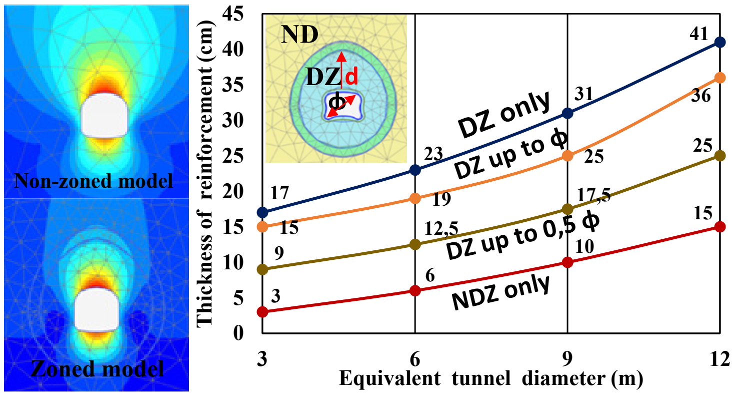

Figure 4. Thickness of reinforcement as a function of the size of the decompressed zone.

3.3 *Zoned model for the empirical tunnel analysis*

The current empirical classification systems consider the different fracture planes as they are observed visually, assuming independence of dimensions and other fixed patterns with depth. That can lead to over-design of the subsurface works. Rock mass valuation indices, such as Barton's Q index or Bienianwki's RMR index, can be adjusted assuming the zoned model for the rock mass. The model can be zoned based on seismic velocities and their relationship to the rating index. After excavation, the observed index corresponds to that of the decompressed zone, but it can be adjusted using a weighted average based on the thicknesses of the three zones (DZ, TZ and NDZ) within an area of influence of the excavation. To avoid assigning greater weight to the non-decompressed zone and based on several evaluations, this work recommends assuming the area of influence up to twice the equivalent diameter of the tunnel.

4 TUNNEL REINFORCEMENT COSTS

The graph in Figure 5 was developed based on the results of the numerical analyses, such as the one indicated in the graph in Figure 4, and using the weighting criteria recommended in the previous point through the equations published by Moreno (2013). These equations allow to determine the total cost of reinforcement per meter of tunnel as a function of the total excavation section and the Bieniawski Index (RMR), applicable for tunnels excavated in the traditional way.

If the tunnel is built in a good quality rock mass, with the non-zoned model, the cost of reinforcement is 80% higher for small diameters and 30% higher for large diameters when compared to the zoned model. In the case of low-quality rock mass, costs are between 35% and 15% higher with the non-zoned model than with the zoned model, depending on the size of the excavation.

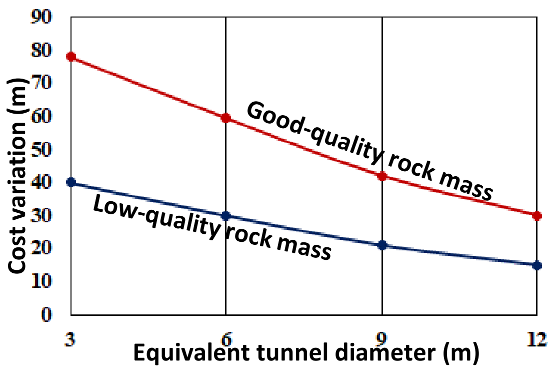

Figure 5. Reinforcement cost variation, analyzed with non-zoned model compared to zoned model.

5 CONCLUSIONS

The term joint, should be redefined for its proper use in geomechanical classification, as non-moving fractures where the extension and frequency depend on the variations of the stress state of the rock mass.

For the geomechanical rock mass classifications, the term discontinuity should allow to differentiate between the formational structural planes, not related to the stress state, and the joints, that actually depend on the regionally and local stresses, in order to perform more realistic geomechanical classification and modeling.

Tunnel excavation will develop joints whose density and extension will be reduced with the distance from the excavation. The resulting decompressed zone, is related to the joint patterns larger size and high density, which has formed due to the highly modified stress state, compared to the zones with small stress changes, occurring beyond the decompressed zone. The joint pattern presented at the tunnel excavation face should not be considered to be the same throughout the rock mass.

The estimated costs for tunnel reinforcement are significantly higher when the rock mass characteristics are assumed to be the same as those observed directly, compared to the results from the zoned models, which allows the modeling of the decompressed zone and the changes in the rock mass quality with respect to the distance from the excavation, according to the seismic velocities, representing a more realistic behavior.

6 RECOMMENDATION

It is recommended to ISRM, to submit for consideration the revision of the term discontinuity, differentiating the continuous formational planes of the rock mass from the joints, which are fractures whose development and frequency depend on the variations of the stress state of the rock mass.

REFERENCES

Brown, E. T. (1981). Rock characterization testing and monitoring. ISRM suggested methods. *Rock Characterization Testing and Monitoring. ISRM Suggested Methods.* https://doi.org/10.1016/0148-9062(81)90524-6

García, E., & García, R. (2004). El Origen de las diaclasas en macizos rocosos y su consideración en obras de ingeniería. In SVDG (Ed.), *XVIII Seminario. Sociedad Venezolana de Geotecnia*.

García, R. (2018). El termino diaclasa y su aplicación adecuada a la valoración de macizos rocosos. *Tekhné*, *21*(3), 71–78.

García, R., Cortesi, A., & Carestia, L. (1998). Análisis de deformación en túneles a partir de ensayos sobre modelos en dos dimensiones. *Boletín de La Sociedad Venezolana de Geotecnia e Ingeniería de Fundaciones*, *58*, 34–38.

García, R., & García, E. (2021). Limitation of the discontinuity designation. A new joint definition according to the stress state in the rock mass. *Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering*.

Moore, D. E., & Lockner, D. A. (1995). The role of microcracking in shear-fracture propagation in granite. *Journal of Structural Geology*, *17*(1), 95–114. http://pubs.er.usgs.gov/publication/70019720

Moreno, M. S. (2013). Predicción del coste de la obra civil de un túnel ejecutado por métodos convencionales. *Obras Urbanas*, *41*, 20–27.

Naime, W., & García, R. (2022). Toward a new definition of terms in the rock geomechanical classification and its relation to the numerical analysis of tunnels. *IX Latin American Rock Mechanics Symposium*.

Naime, W., & García, R. (2023). The rock mass and the development of joints during the tunnel excavation. *IOP Conference Series: Earth and Environmental Science*, *1124*(1), 012058. https://doi.org/10.1088/1755-1315/1124/1/012058