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Limitation of the discontinuity designation. A new joint definition according to the stress state in the rock mass

Limitation du terme discontinuité vers une définition de diaclase en fonction des tensions dans le massif rocheux

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ABSTRACT: The International Society of Rock Mechanics defines a mechanical discontinuity in a rock mass as a structure with very low or zero tensile strength. This definition does not differentiate stratification and foliation which are formational planes. In turn, the joint designation is defined as non-movement fractures and whose development depends on the stress state, which is related in the current mechanical classifications of the rock mass by having constant geometric dimensions could be far from reality. Further, the persistence or extension of the joint plane, which originated from micro-fractures in the rock mass and its development is generated by the stress changes, is not constant. This work shows a new approach for the proper use of geological terms in relation to the stress changes and not as constants numbers in the rock mass evaluation, which has a significant impact on the costs of the engineering works.

RÉSUMÉ: La Société Internationale de Mécanique de Roches définit une discontinuité mécanique dans une masse rocheuse comme une structure avec une résistance à la traction très faible ou nulle. Cette définition ne différencie pas la stratification et la foliation qui sont des plans de formation des roches et pas d'origine mécanique comme les diaclases. A son tour, une diaclase est définie comme une fracture sans mouvement et elle est liée, dans les classifications actuelles des masses rocheuses, à des dimensions géométriques constantes, ce qui peut être très éloigné de la réalité, car le développement dépend des tensions dans le massif rocheux. En plus, la persistance ou l'extension du plan de la diaclase provient de microfractures dans le massif rocheux, où le changement de tension génère le développement du plan, donc la persistance n'est pas constant. Ce travail montre une nouvelle approche pour la bonne utilisation des termes géologiques en relation avec le changement de la tension dans la roche, et non comme de simples chiffres dans l'évaluation du massif, ce qui a un impact significatif sur les coûts des travaux.

KEYWORDS: joint, discontinuity, microfractures, microfisures, persistence, development, frequency, rock mass.

1 INTRODUCTION

The joints in the rock mass are defined by the International Society of Rock Mechanics (ISRM) 1981 as any mechanical discontinuity that has zero or very low tensile strength. It is the collective term for most joints, weak stratification planes, weak shalese planes and those within failure planes. The above definition has led worldwide to errors in the assessment of the rock mass, with significant cost oversteer in engineering works, but with a high safety factor.

In the evaluation of the rock mass, it is important to differentiate the origin of the formational planes, such as stratification and foliation, which do not correspond to the mechanical effects on the formation of the joints. Likewise, joints depend on the stress state in the rock mass, just as the development of any crack in a structure can reach important dimensions when its confinement conditions change.

It is important to consider the stratification and foliation planes as terms associated with the classification of rocks according to their origin, in sedimentary and metamorphic, respectively. They are continuous planes that control mechanical behavior according to the request in the rock mass.

The definition of the term joint in the classical books of Structural Geology (Krynine & Yudd 1961; Legget R. 1965; Billing 1954) is indicated as non-moving fractures and there may be separation perpendicular to the plane that then corresponds to the opening. Ramírez O.P. and A. Mange (2004) define joint in a series of intact rock blocks or elements and a structure formed by multiple discontinuities. In general, joints are considered by different researchers as fixed patterns with representative and uniform characteristics in the rock mass, associated in parameters for classification, mainly related to tunnelling works.

2 DEVELOPMENT OF JOINTS

The engineer related to both surface and underground excavations, considers the term joint as fractures without movement, according to constant dimensions and patterns. The definitions of joint, existing in extensive documentation could be far from reality. García R. (2018), analyzes the development of the plane that defines the extent of the joint according to the confinement, depending on its extension to the tension state of the rock mass, represented in schematic form in Figure 1.

The above can be visualized in numerous examples, starting with excavations of high cutting slopes, whose follow-up over time, show the increase in the development of joint on the surface of the slope. Likewise, the fracturing presented by the excavation front of a tunnel is largely due to the change of tensions of the rock mass, where the patterns of joints develop from microfractures.

2.1 The formation of joints

Joints in rock mass are closely related to the principles of fracture mechanics and the breakage criteria described by different authors. Arana and González (2002), mention it in accordance with Von Mises, Mohr-Coulomb, Tresca, Hoek-Brown and Drucker-Prager, among others, as well as Griffith's breakage criterion (1923), very useful in explaining why certain fragile materials break under lower stresses than would be expected. On the Griffith's energy balance it was studied the fracture conditions of fragile solid bodies with cracks, establishing the initial theory underpinning fracture mechanics. He proposed a fracture formation model, according to which everything was due to small microscopic breaks caused by concentrations of stresses in micro-cracks or imperfections of the material, which are joined (propagating) with each other until it causes the breakage.

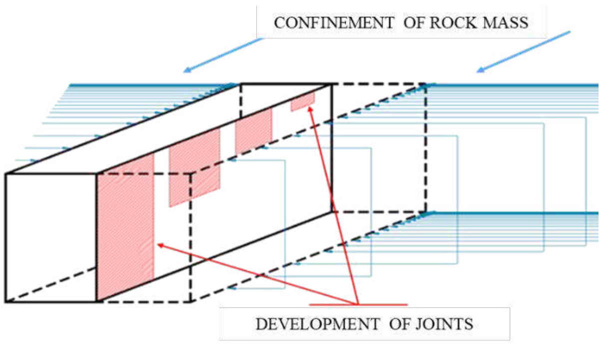

Figure 1. Variation of joints development according to the rock mass confinement.

Although Coates (1970) indicates that Griffith's theory is unlikely to be applied to rock mechanics, when we look at a rock sample under the microscope, the presence of microfisures, which will control joints patterns in outcrops. Figure 2 shows schematically the passage of microfisures at the microscope level, as well as the passage to microfractures that can be visually identified with a magnifying glass and finally, the joint at the macro level of outcrops.

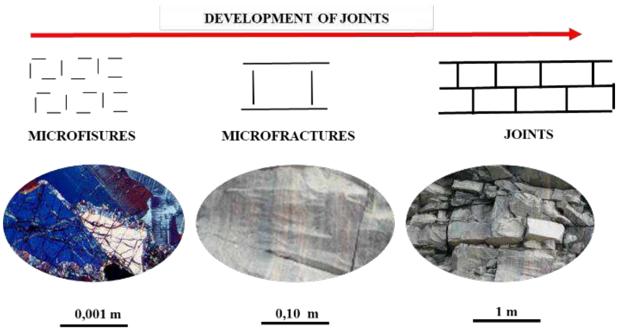

Figure 2. Differences between microscopic microfisures, macroscopic microfractures and joints.

2.2 Rock mass and joints

The effects on the formation of microfisures and microfractures should be visualized regionally, where efforts are involved on large masses of rock, whose mechanical behavior depends on the volume of the sample. The formation of the joints is outlined in Figure 3, where both geo-static loads, as well as tectonic forces acting on a rock mass, cover regional lithological masses The mechanical behavior of these is related to a confined state of stresses, associated with an elastoplastic mechanical behavior, where mineralogical components are affected by microfisures. The latter are only visible in microscopic petrographic observations. Erosion processes cause a change in the confinement efforts of the formational mass, with decompression effects. Some of the microfisures develop to microfracture patterns, whose orientations depend on the change of stress stresses in the rock mass. Following regional change with the decrease in confinement efforts, some of the microfractures, oriented according to patterns, develop the joints systems.

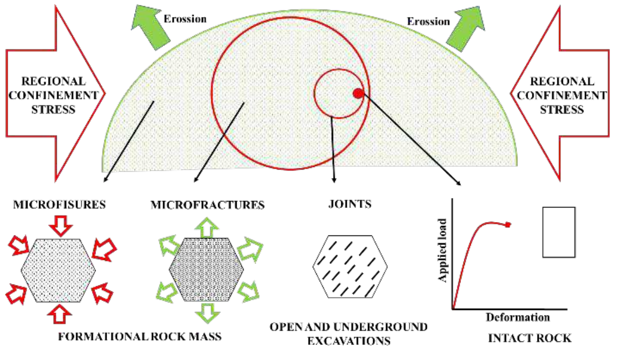

Figure 3. Scheme of mechanical behavior in accordance of the strength suffered by the formational rock volume and microfisures, microfractures and joints that are created in consequence.

When the development of microfractures to joints is generated, during the local involvement of the rock mass by changes in the state of stress, as well as in the case of excavations both open and underground, the predominant orientation will depend on the greater tension which must correspond to the face of the excavation.
For the case of an intact rock sample, its behavior is elastic with a fragile fracture. In this case, microfisures are only visible in microscopic images of fine sections on rocks, which even affect minerals while maintaining certain patterns. Microfractures must be caused by changing the tension state of the rock mass, and may be associated with some sectors with mineralogical variations affected by microfisures. An unconfined compression test, as indicated by Ramirez and Mange (2004), is a progressive process that leads to the formation, propagation and coalescence of micro-cracks.

3 PERSISTENCE VERSUS DEVELOPMENT OF JOINTS

Persistence refers to the length of the joint plane, which classification recommended by the International Society of Rock Mechanics (ISRM) according to Brown (1981), varies with terms from very small when it is less than 1 meter, to very large when it is greater than 20 meters. The development of the joint depends on the stress state of the rock mass, which is evident in detailed surface observations, including open pit and underground excavations.
One of the effects on the tension change of the rock mass, should be attributed to weathering, as seen in Figure 4. It details a drilling carried out during the investigation of a dam site on the Cuira River, Edo. Miranda, Venezuela. In the rock cores shown in the drill box, it is highlighted that the fracturing decreases with the depth. Likewise, it is observed that fracture systems have high frequency in the first meters, where the rock is weathered with the existence of oxidized planes, decreasing their frequency with depth as the physical condition of the rock changes to fresh. This ensures that below the areas affected by the weathering, already in fresh rock condition, there is a high quality of the rock mass associated with very low permeability, that important conditions for the foundation of a dam.
During tunneling, excavation fronts often have an non-representative pattern of fractures as we move away from the perimeter of the excavation. This is evident in the results of research conducted with micro-seismic tests, where the so-called decompressed zone is delimited.
In excavation slopes, joints systems are well exposed and developed due to a complete release of the confinement of the rock mass. It is considered that in a confined massi, there is a predominance of microfractures, which with the change of effort develop to joints systems. Therefore, the term persistence does

not seem like an appropriate term because the joints systems are developed according to the change in the stress state of the mass., being more useful the term development, indicated by García R. & García E. (2004).

Figure 4. Core simples obtained during exploration works of Cuira Dam site, Miranda State, Venezuela.

3.1 Outcrops and joints

A good example of the development of the joints is found on the steep ourcrops at Angel Falls in Bolivar state, Venezuela. Being the highest waterfall in the world, with about 1000 meters of elevation, the rock mass is controlled by a sequence of layers of silicified, solid sandstones, with individual thicknesses of more than 10 meters, whose age is considered pre-cambric. The outcrops are controlled by vertical joints, whose persistence is limited to layer's thicknesses, which guarantee their stability. This forms a sort of ladder, due to the lack of continuity of fractures from one layer to another, where the lower blocks support the upper ones. When we move from the outcrop to inside the rock mass, the joints that are generally open, close and acquire less length. Figure 5 shows a Google Earth image of Angel Falls, showing the formation of joints from micro-fractures, whose persistence or development is not constant, decreasing with confinement.
In conclusion, the persistence in a rock mass is not constant and depends on the state of tensions of the mass, being the term development the most suitable.

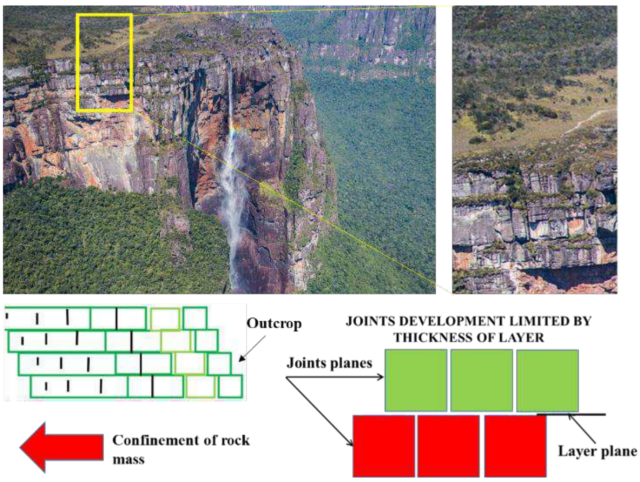

Figure 5. Detailed view of outcrop at Angel Falls (Venezuela) compounded by siliceous sandstones layers where the development of joints is limited to the thickness of layers.

4 FREQUENCY OF JOINTS

It is called frequency or spacing of the joints at the mean distance between them, usually represented by the number of joints within certain segment perpendicular to the measuring plane. The terminology of the spacing recommended by the International Society of Rock Mechanics (ISRM), indicated by Brown (1981), highlights the terms as extremely closed when is less than 2 cm, closed between 6 and 20 cm and open between 60 cm and 2 meters, it is important to note that spacing is associated by Brown in the term of discontinuity.
Sedimentary rocks are made up of layers, limited by planes of infinite extent, due to their formational origin. Similar condition occurs in metamorphic rocks with foliation planes whose cementation controls a condition similar to a layer, such planes being less than 2 centimeters.
It is of great importance to differentiate the formational planes according to the simple classification of the rocks according to their origin, where fractures are subsequent mechanical effects.
Joints patterns in sedimentary and metamorphic rock sequences are limited to layer thickness or cementation in foliation planes, respectively. It is important to note that when there are lithological variations limited by low resistance planes, such as foliation or stratification planes, these generally limit their development. Figure 6 shows a sequence of sandstone layers that control steepness on the coast in Pampatar area in Margarita Island, Venezuela. It can be detailed higher frequency of joints in smaller layers, with sandstone layers being the thickest. There is also an offset in the continuity of the joints with no continuity with the top or bottom layer.
Something similar happens in metamorphic rocks, according to the cementation of foliation planes, where the highest frequency of joints is observed in thin cemented intervals. Joints are limited in their development to the cemented foliation package, the continuity of which is interrupted from one package to another, in general when cementation decreases where the continuous plane that defines foliation is well exposed.

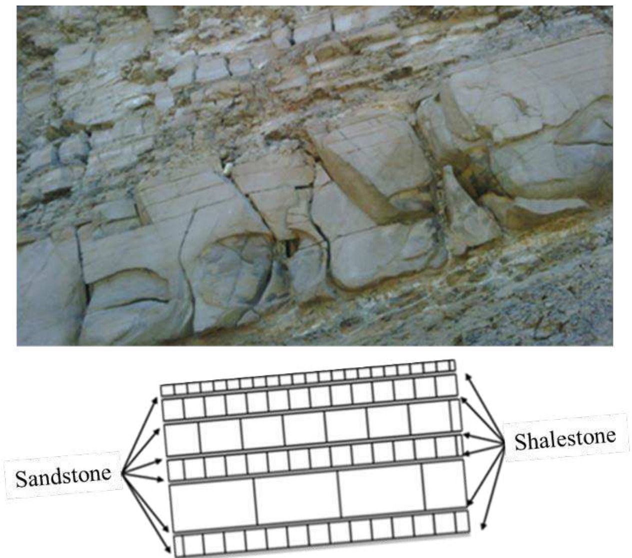

Figure 6. Differences in joints frequency according to thickness of layers.

4.1 Granitic rocks and joints

A uniform, fresh looking granite rock mass can react to the change in effort when excavated, and become a fractured mass, where standing out in the planes that limit fractures, it will be highlighted a rough and shiny surface. The change of effort in the mass develops the joints from microfractures. During the excavation of the discharge channel of the Tocoma dam, on the Caroní river, Edo. Bolivar, Venezuela, see upper photo at Figure 7. The rock mass is made up of granite rocks, classified for the construction bidding purposes with 100% RQD. Some excavation fronts of the discharge channel were observed to be very fractured, with the presence of sub-horizontal joints. They resembled layers, with recreation or frequencies of three (3) in one (1) meter, which were octagonally cut by patterns of sub-vertical joints. In the photo below you can see details of the different patterns of fractures, bright surface and rough to the touch, similar to fractures generated by mechanical effects.

It is remarkable on this place, the development of joint patterns with a sub-horizontal main system that limit other orthogonal. The excavation of this discharge channel is limited by slopes about 30 meters high, being located at 200 m distance of the great channel of the Caroní river. The rock mass did not present leaks, being classified as non permeable. The formation of sub- horizontal joints may have its origin of horizontal microfractures due to the effect of large vertical loads, released due to the impact effects of blasting during excavation. In addition, orthogonal vertical patterns may have a post-horizontal microfracture origin, which would limit their vertical development.

In the excavation of tunnels in non althered granite rocks at high depths, it is remarkable the occurrence of explosive effects on the rock as a result of the presence of microfisures, which develop to jointse where the patterns are oriented parallel to the tunnel axis and subhorizonal according to the excavation surface. Subsequently, vertical fractures parallel to the tunnel axis are developed, being delimited the rock in the form of beams or columns. The bending effect on the rock delimited by the joints eventually produces its burst.

5 ROUGHNESS

Roughness is a term that associates friction between blocks that limit the fracture area. It is used by ISRM (Brown 1981) in discontinuity planes, where it includes the formational planes of rocks, such as stratification in sedimentary rocks and foliation in metamorphic rocks. In general, joints are straight planes that cut the rock mass, which can be differentiated from large-length formational continuous planes and which do not adapt to the classification proposed by the SIMR.

This classification covers two scales, one intermediate of several meters long that comprises three (3) degrees of roughness (staggered, wavy and flat), which is combined with a small scale in centimeters Additionally, it includes three (3) degrees of roughness: rough, smooth or soft and polished or fault mirror. Given the above, the classification combines nine (9) degrees of roughness. This should be used with a detailed criterion within the term joint; a polished surface or fault mirror, is a geological fault defined as a moving fracture.

Similarly, the undulating planes of great development correspond to the characteristic foliation planes of metamorphic rocks, as well as the contact planes of different layers of sedimentary rocks, which have irregularities by effects of the loading sequence.

5.1 Roughness and resistance

Roughness is a term of great importance because of the effect of friction resistance to displacement that is generated between rock surfaces that limit the joint plane. It is closely related to the size of minerals and/or fragments of the mineralogical composition, as well as to chemical alteration on the surfaces of rocks that limit the plane. If the rock is made up of very fine or aphanitic grain size, the fracture or joint shall be bounded by a soft-touch rock surface, instead if the rock is made up of thick grains, the surface will be uneven. For shalestones consisting of clay mining, the surface of the joint plane is smooth, with very low friction. In contrast, for the case of sandstones, consisting of sand granulometry, the joint plane usually has a rough surface. In the granitic rock in Figure 7, the surfaces of the fracture planes are presented with jumps and irregularities, which under confined condition must act as elements of high-strength locks, which can be related to high cutting resistance.

Roughness also depends on the degree of mineralogical alteration in the plane that limits the joint, where the loss of resistance of the minerals decreases friction between the planes. Also the filling by fine particles in the joints' planes controls its resistance, if it is clayey its resistance is low, instead if it is sandy, the friction is greater.

The roughness of the joints can be estimated by passing the palm of the hand on the surface of the rock, being able to feel the actual characteristics of its irregularity and evaluating the friction conditions in high, medium or low terms. A common test is to place one block on top of another, increasing its inclination until the displacement occurs, corresponding to the angle obtained from the friction value.

6 OPENING AND FILL OF JOINTS

The opening of a joint is the perpendicular distance between rock walls that limit the fracture plane. The terminology recommended by ISRM (Brown 1981) considers three aspects: closed, slit and open.

Figure 7. Excavation in the Tocoma discharge channel, estado Bolívar, Venezuela. Igneous rocks mass with the presence of sub-horizontal joint patterns, limiting sub-vertical joint planes.

The closed classification aspect is at the same time sud-divided into three conditions: less than 0.1 mm, 0.1 to 0.25 mm and from 0.25 to 0.5 mm. A 0.1 mm opening must be associated with a development of similar dimensions, being only visible in observations by a petrographic microscope. Joints can be observed under simple sight when their dimensions are greater than 0.25 mm, being their opening related with their development. When slit openings are indicated, the indicated range is between 0.5 to 10 mm, standing up to a rock outcrop. A joint of (1) centimeter of opening is very important, being able to be related to the effect of changing the stress state, with a trend to get closed a few meters from the surface.

The opening of a joint must be related to the appearance on the surface of its walls, which may look bright on the planes that delimit it or have an opaque appearance, where atmospheric agents have acted. From the first observations it can be concluded that the opening is the result of a change of stress conditions in the rock mass and that the joint can be found in microfracture dimensions a short distance from the surface. When the planes of fractures are observed opaque or associated with oxides, the passage of water is evident, corresponding to a fractured mass, where joints are open, as evidenced in the drilling samples in Figure No5. In the first meters, the rock mass is classified as highly fractured, possibly related to effects of weathering and the presence of microfractures, which generate a high density of joints.

6.1 Joints fill and breccias

On the filling of the joints, it is important to note that to fill the them these must be open, allowing the flow of water to circulate and deposit the materials that may be dissolved within the flow. In some cases, large aperture joints can be filled with material transported by rock erosion effects at a upper level.

The main filling of the joints planes is related to the passage of groundwater, whose variation in the water table precipitates on the walls films, generally related to oxides. When water is rich in carbonates or sulfates, the solutions fill the joints with calcite or gypsum, the identification of these fillings is very important in dam foundations, whose dissolution in the presence of permanent water flow, will increase the permeability of the mass over time. The presence of significant thicknesses of clay fillers is unlikely, as the underground flow is associated with solutions and their precipitation on the joint plane. Within a rock mass, the presence of clay between rock planes is associated with tectonic effects due to geological faults, which movement crushes the materials of the walls, forming gaps of very low resistance. Likewise forming the so-called fault mirrors or polished surfaces due to great tectonic stresses, they should be differentiated from the joints.

In a rock mass below the area of mineralogical alteration, the joints tend to close, generally without oxidation effects, changing in turn with the depth to a fresh, non-permeable confined mass. Regional tectonic effects can cause stress efforts on the rock mass, developing sectors with open joints that control water accumulation. Likewise, part of the oil and gas deposits in sedimentary rocks sequences are related to secondary permeability due to fracturing in the rock mass, mainly due to the formation of folds.

7 ERRORS IN GEOTECHNICAL CLASSIFICATIONS

In the existing geotechnical classifications of the rock mass, the term discontinuity associates joints and continuous formational planes of the rocks, stratification in sedimentary and foliation in metamorphics. Joints are mechanical effects on the mass, defined as non-moving fractures. In addition, joints patterns are considered constant in the rocks, which is far from reality, due to the dependency of development and frequency of patterns on the state of efforts. Observing an exposed surface of a rock mass, persistence and frequency are the result of a change in the state of confinement, which is evident in seismic or micro seismic aassessments, where speeds increase with confinement. This is due to a change in stresses in the rock, partly as a spongeing behavior that develops joints. Micro seismic research in tunnels, basically measuring longitudinal and transverse speeds, delimits an area called unzipped or deconfined. In these tests a constant speed is reached with depth. From numerous research carried out in tunnels, a schematic model is proposed shown in Figure 8, where the development of the joint is related to seismic speeds, which increase as we move away from the open faces. In the empirical classifications of the rock mass, mainly used in tunnel design: Wickhan RSR, Tiedeman & Skinner (1972), Barton Q, Lien, and Lunde (1974), Bieniawski RMR (1974, 1979 and 1989), 75% of the value of this classification depends on joints systems, whose observations are based on the exposed surface, where these systems are developed. Seismic speeds increase with depth, being representative of a confined massif generally affected by microfractures.

The lack of knowledge in geological structures has led different professionals to perform geotechnical classifications based on a number or magnitudes that can be far from reality. An understanding of the origin and development of the joints will allow to quantify in real form the mechanical properties of the rock mass, which vary according to the state of stresses.

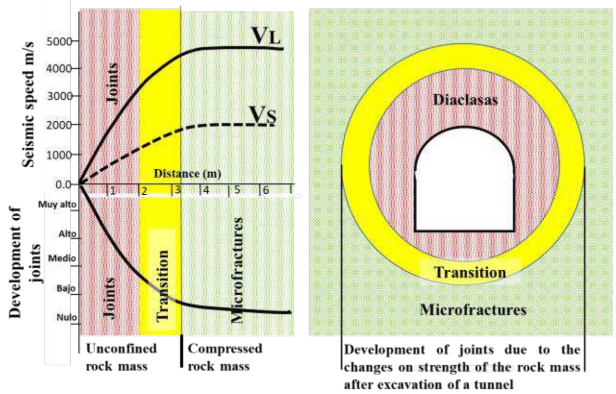

Figure 8. Scheme model of development of joints during the excavation of a tunnel, according to micro seismic velocities VL and VS.

8 CONCLUSIONS

The development and frequency of the joints depend on the confinement state of the rock massi. Therefore, their geomechanical classification is not unique. All observations on the surface of the rock mass represent very different stress conditions from a mass when confined, where the joints will be less developed, being able to reach dimensions of microfractures.

- In sedimentary and metamorphic rock sequences the stratification and foliation planes are part of the classification of the rocks according to their origin, which although included in the term discontinuity defined by the SIMR. They constitute particular planes of great extension and mechanical behavior very different from the joints.
- Joints are well developed towards the surface of the Earth's crust, usually associated with erosion and weathering effects. Its frequency is higher in the weathered rock, decreasing to depth where its physical condition is classified as fresh. Likewise, the frequency of joints is related respectively to the thickness of layer or cemented foliation, being the highest frequency in thin layers.
- The presence of gaps or polished planes is related to movement in geological faults, being particular geotechnical conditions of stress, far from their relationship with the joints. The filling in the joints is related to their opening, through which water flows,

depositing materials in solution such as oxides, carbonates or sulfates.

- The roughness of the joints depends mainly on the size of grain or mineral that forms the rock. In fine grain, the surface to the touch is generally smooth, contrasting with the thick grain rocks of rough surface that generate high friction at the displacement of the blocks.

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