Considerations about failure mechanics of weathered foliation surfaces

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ABSTRACT: Based on some experiences gained from observations of landslides and analysis of shear tests along foliation surfaces, this paper deals with some considerations about failure mechanics of weathered metamorphic rocks. Use of different terminology is discussed, calling attention how some definitions may lead to confusion and misunderstanding. The need for a correct field characterization is emphasized, and problems that could arise when dealing with meta-sedimentary rocks subjected to various generations of superimposed foldings, are described. Finally, based on interpretation of direct shear tests, a failure mechanism is proposed to explain shearing along weathered foliation surfaces of phyllites. In order to explain differences between peak and ultimate strength, not expected on smooth planar foliation surfaces, the proposed mechanism describes the development of a stepped profile created during shearing by tensile rupturing of the weathered weak rock, apparently facilitated by an incipient crenulation cleavage.

1 INTRODUCTION

Metamorphic rocks of sedimentary origin outcropping in the mountains of the Coastal Central Range of Venezuela, show a very well developed foliation surfaces which orientation is responsible for the occurrence of many landslides. Every year these landslides cause important property damages and loss of lives in urban developments located on the hills. Description of this problem has been reported by Salcedo (1982, 1983, 1984). Catastrophic landslides affecting hills in Caracas, capital of Venezuela, have been also published by Schuster, Salcedo & Valenzuela (2002).

Many of the metamorphic outcrops show mainly weathered quartz-mica schists, quartz calcareous schists and quartz-sericitic mica phyllites, with some lenticular marbles. Results of weathering tests on some of these rocks have been published by Gómez Da Silva, Aires Barros & Salcedo (1993).

Phyllites have typically light gray color, smooth surfaces and unctuous talc-like structure. Due to the low shear strength along foliation planes, failure surfaces are mainly controlled by this lithology, and therefore there is a need to understand the failure mechanics along weathered foliation surfaces in the aforementioned phyllites. This paper discusses terminology, field characterization and shear strength aspects, related to weathered metamorphic rocks.

2 TERMINOLOGY

Use of the same terminology in rock mechanics literature is an essential step towards sharing knowledge about shear behavior of discontinuities. This is a difficult task because the terminology problem arises due to the fact that some researchers use genetic definitions and some use descriptive nomenclature rather than genetic.

The term foliation has been used with different meanings by geologists and civil engineers and considerable current ambiguity attends its use. Foliation is considered synonymous with “flow cleavage”, “slaty cleavage” and “schistosity” by many authors to describe parallel fabrics in metamorphic rocks. On the other hand, some authors as Hobbs, Means & Williams (1976) use the term foliation in a broad sense to describe compositional layering, grain size variation, closely spaced approximately parallel discontinuities such as microfaults or fractures, preferred orientations of grain boundaries, preferred orientation of platy minerals or lenticular mineral aggregates, and combinations of the various microstructures. According to this definition, the word foliation is applied either to sedimentary or to metamorphic rocks and even to igneous rocks. This latter definition of foliation is confusing and from a shear behavior point of view, each of them should be treated as a separate feature.

In order of metamorphic intensity the rocks formed are slate, phyllite, mica schist and gneiss. In this sense the term "slaty cleavage" is mostly used for less intensely metamorphosed rocks such as slate, whereas "schistosity" is employed if the rock is recrystallized into minerals that are readily recognized by the naked eye (Billings, 1972). Theoretically, a rock possessing slaty cleavage can be split into an indefinite number of thin sheets parallel to the cleavage. Schistosity has been also defined as the variety of foliation that occurs in the coarser-grained metamorphic rocks (AGI, 1974).

The writer prefers the use of the term foliation in a more restricted sense to describe surfaces with parallel arrangement of platy and tabular minerals or parallel arrangement of ellipsoidal grains such as quartz or feldspars, due to a process of metamorphism. This definition restricts the use of the term foliation to metamorphic rocks. Figure 1 shows a typical outcrop of phyllites with well-developed foliation, and Figure 2 shows a thin section of a phyllite with very well developed foliation due to preferred orientation of micas between quartz bands.

Medium metamorphic grade rocks, such as phyllites, may also have what it is known as "crenulation cleavage" which can be defined as closely spaced microfaults or microfractures that divide the rock into a series of tabular bodies, approximately planar. Other terms such as "shear cleavage" or "slip cleavage" have been also used in the structural geology literature. Some authors prefer to use, in a general way, the term "fracture cleavage". As pointed out by Billings (1972) the terminology applied to the various kinds of rock cleavage has evolved over many years and consequently some confusion and lack of complete uniformity is inevitable.

Concerning terminology it is also important to mention that many geotechnical publications use the term "joint" referring to all kinds of discontinuities such as true joints, bedding and also foliation. It has to be pointed out that foliation has a different geologic origin than a "true joint". From a geologic point of view "joints" are fractures without lateral displacement, originated by tectonic stresses. On the other hand, foliation as described above, refers to surfaces where platy and tabular minerals have been oriented in a parallel arrangement by a process of either contact, static or dynamic metamorphism which implies particular conditions of temperature and pressure. In summary, according to the writer the use of the term "joint" is not adequate for all kind of discontinuities in a rockmass and leads to misunderstandings. In this way, the term "discontinuity" is preferred when it is necessary to make reference to all of these terms together. Based on these ideas it is reasonable to think that shear behavior of foliation surfaces and true joints should be individually investigated, even though some failure mechanisms are similar. Salcedo (1984) concluded that "open joints theories" (Patton 1966, Barton et al 1977, Ladanyi & Archambault 1970) did not fully explain the sliding mechanism of some landslides along foliation planes of weathered phyllites.

Figure 1. Outcrop of weathered phyllites showing well-developed foliation and a low persistence joint.

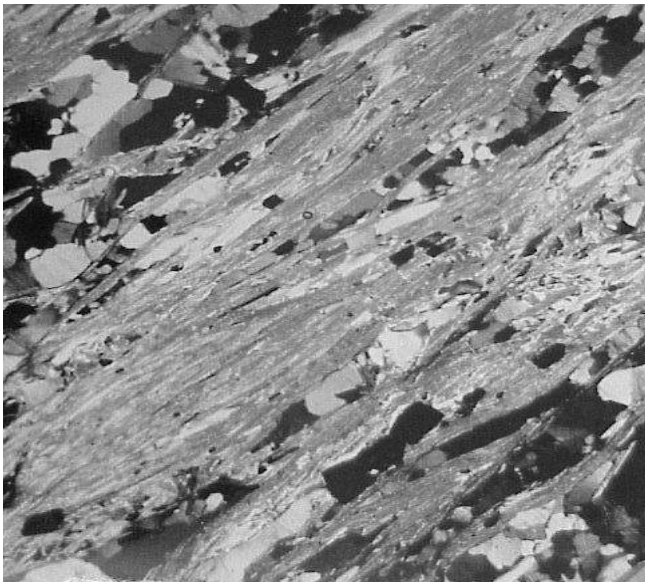

Figure 2. Thin section of a phyllite showing a well-developed foliation due to preferred orientation of micas between quartz intervals. (1.5 cm in photograph = 1 mm).

3 FIELD CHARACTERIZATION OF METAMORPHIC ROCKMASSES

An additional important step towards understanding failure mechanics of landslides in metamorphic rockmasses, is to accomplish a correct field characterization. In most igneous and sedimentary rockmasses, field characterization could be generally be considered a relatively easy task and any geotechnical engineer could accomplish such work with an adequate knowledge of basic geological concepts.

Dealing with metamorphic rock masses transformed from sedimentary rocks (meta-sedimentary rocks) characterization may appear to be simple but the final interpretation of collected data without some geologic knowledge, may lead to interpreted subsoil profiles that differs largely from the real ones and, as a consequence, to serious mistakes in the engineering decisions. For example, when metamorphic rocks are formed from sedimentary rocks and the grade of metamorphism is low, the original textures of bedding could be still evident. Under this condition a non-expert geotechnical engineer may confuse bedding and foliation in different outcrops and characterization may be erroneous. Goodman (1993) discusses why slaty cleavage should not be confused with bedding in rocks that possess both structures.

Metamorphic rock masses of the Central Coastal Range of Venezuela, for example, have been subjected to at least three generations of superimposed folding. These processes produced refolding of previously folded rock resulting as a consequence, extremely complex geometric forms that must be preferably characterized by an expert field geologist.

Figure 3 shows foliation surfaces and original bedding in two different metamorphic rock samples. In these cases foliation surfaces have been developed and oriented parallel to the axial planes of the originally bedding folds. This is a very important observation because if a shear failure has to be analyzed along the foliation surfaces, it must be taken into consideration that shearing could be occurring along different lithologies; therefore, the shear strength parameters have different values along the failure plane. In other words if the original sedimentary rocks was formed, for example, by alternating layers of sandstones and shales, due to the process of metamorphism these rocks are transformed into quartzites and slates (or phyllites or schist depending on the intensity of metamorphism), respectively. This means that friction angle and cohesion will vary along the failure plane and some hypothesis must be accepted for slope stability purposes, in order to take this fact into account. Any hypothesis needs of course, a clear understanding of the geological history of the rockmass under consideration.

Taking into account that foliation is generally a non-persistence discontinuity, the aforementioned reasonings complicate even more the problem of analyzing rock slope stability in this type of discontinuity. As it is well known this problem is related to difficulties of measuring persistence and the fact that peak resistance of intact areas and on the discontinuity, are not mobilized simultaneously.

Shear strength of non-persistent discontinuities and the effect on rock slope stability have been previously discussed by several researchers such as Lajtai (1969), Jennings (1970), Stimpson (1958), Von Thun (1975), Einstein et al (1983), and recently by Gehle & Kutter (2003).

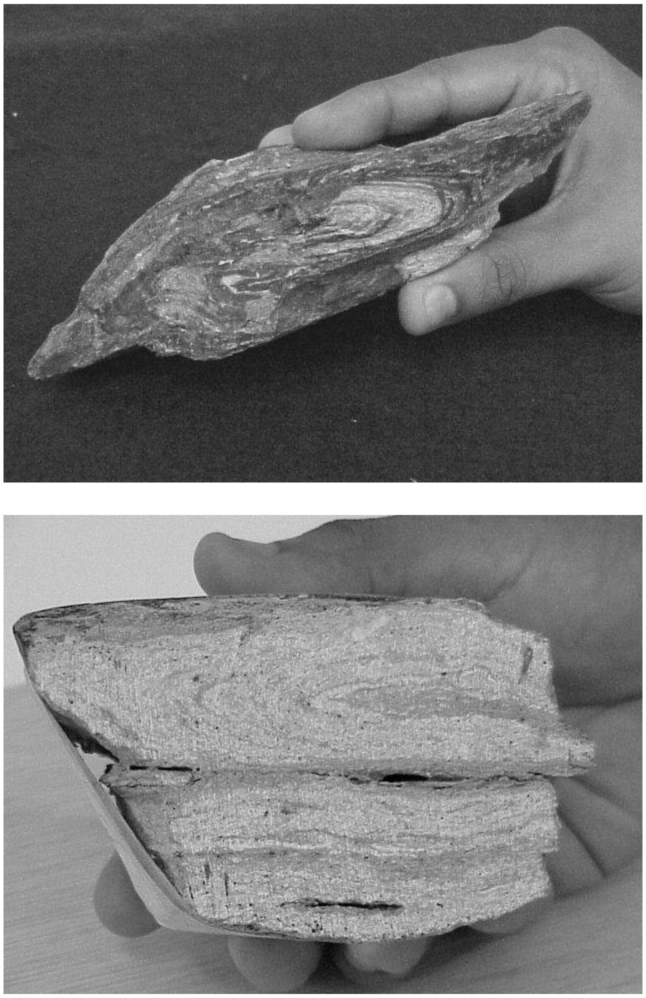

Figure 3. Samples of schists showing foliation planes parallel to axial planes of originally bedding folds.

4 SHEAR TESTS ALONG FOLIATION SURFACES IN WEATHERED PHYLLITE

Based on the fact that most landslides in the Central Coastal Range of Venezuela are controlled by the orientation of foliation surfaces in weathered phyllite, twenty-nine shear tests along these surfaces were run in samples taken from landslides areas. Twenty samples had closed foliation surfaces, and nine samples had open foliation surfaces (100% persistence). It has to be noted that the term “closed foliation” used herein, does not mean that the entire surface is “non-penetrative” or “non-persistent”. Closed foliation surfaces may have areas in contact without any tensile resistance in the direction normal to them.

Direct shear testing was accomplished by means of a field shear equipment manufactured by Robertson Research Laboratory, described by Hoek & Bray (1974). Samples were essentially rectangular with length between 7 cm and 12 cm, and width between 5 cm and 9 cm. After obtaining the shear stress-displacement curve up to a maximum displacement of 5 mm, a multiple reversal test under different normal stresses was subsequently performed on the same failure surface.

The phyllites tested have an average unit weight of 21.5 KN/m^3, and an estimated unconfined compressive strength ranging from 1.1 MPa to 7.0 MPa. Quick absorption tests results (Hamrol, 1961) vary between 9% and 10%.

During field work it was noticed that only some of the monolithic samples showed open foliation surfaces but most of them showed closed foliation surfaces (See Figure 4).

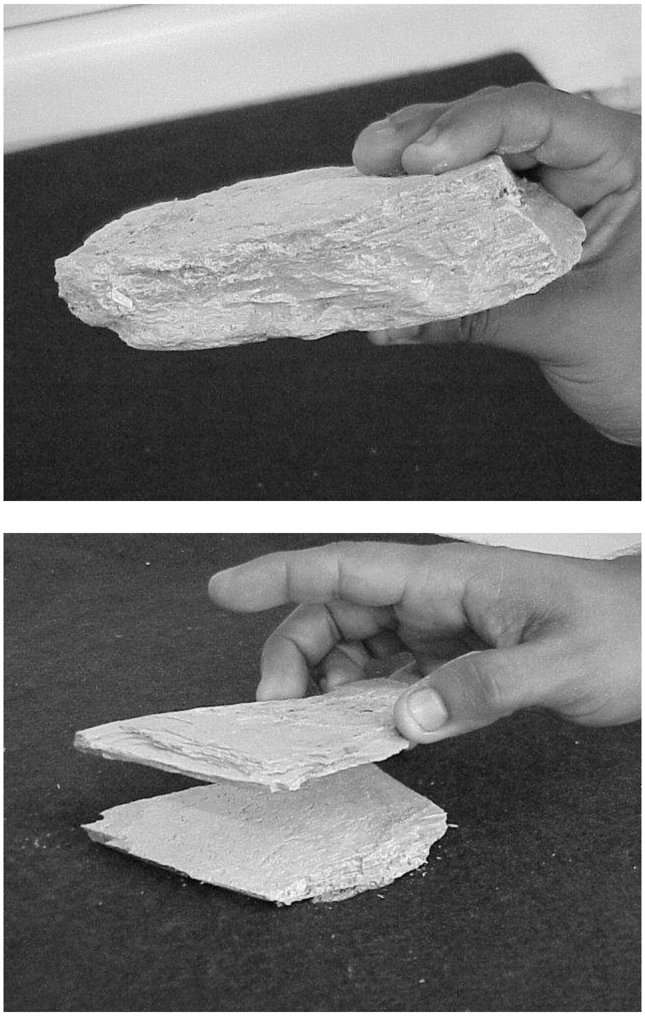

Figure 4. Samples of phyllite with closed and open foliation surfaces.

It was also noticed that some of the closed foliation samples broke apart very easily exhibiting very low tensile strength in the direction normal to foliation surfaces. Other samples could be broken apart if enough hand pressure was applied perpendicular to foliation. Finally, there were pieces of the foliated rock that could not be broken parallel to foliation surfaces even with strong hand pressure. This behavior clearly reveals that closed foliation surfaces are composed of “unfractured” or intact areas and “fractured” areas in contact. Taking into consideration that foliation is not really a “fracture”, it seems to be more correct to state that there exist areas where the foliation is “penetrative” (100% persistence), and other areas where foliation is not “penetrative” (non-persistent).

The ratio of “penetrative” to “non-penetrative” areas depends on the geological history and mainly on the stress deformation characteristics of any particular location within the folded metamorphic rock. It is obvious that the ratio of these areas determines the strength of a particular specimen, which varies depending on its location.

Sericitic phyllites tested also have an incipient crenulation cleavage that consists of parallel surfaces of secondary origin as can be seen in Figure 5.

Figure 5. Incipient crenulation cleavage developed in a sample of sericitic phyllite.

4.1 *Peak strength*

Figure 6 shows peak strength direct shear test results for closed foliation specimens and peak strength for open foliation specimens. It can be seen that in terms of Mohr-Coulomb theory a straight line can be drawn to characterize the behavior of the open foliation surfaces, however, it is impossible to establish a unique relationship for the closed foliation surfaces. These results were expected and the wide range of peak values obtained for closed foliation surfaces confirm the variability observed during field characterization regarding the different strengths along foliation surfaces of individual specimens. In Figure 6 a straight line envelope has been fitted to results of open foliation surfaces which results in a friction angle of 29º and zero cohesion. A series of parallel lines to the open foliation surfaces envelope has been fitted in Figure 6 to results of peak strength of closed foliation surfaces, resulting interpretation showed in Figure 7. This is just a rough interpretation in terms of Mohr-Coulomb theory, based on the hypothesis that envelopes of an individual family of closed foliation surfaces have friction angles approximately equal to the one obtained in open foliation surfaces which is not necessarily true.

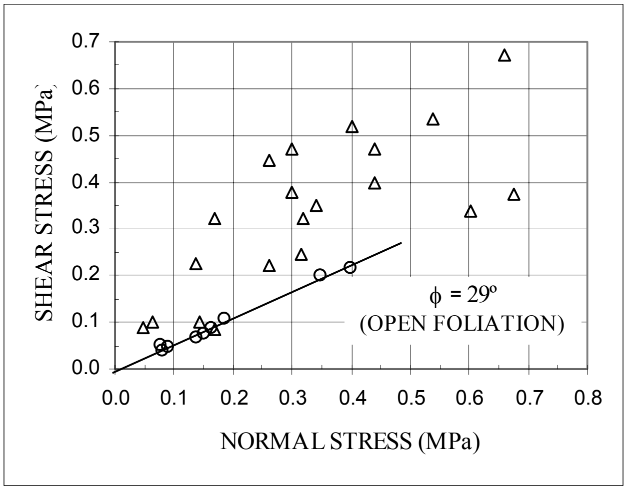

Figure 6. Peak strength results of open foliation surfaces (circles) and peak strength of closed foliation surfaces (triangles).

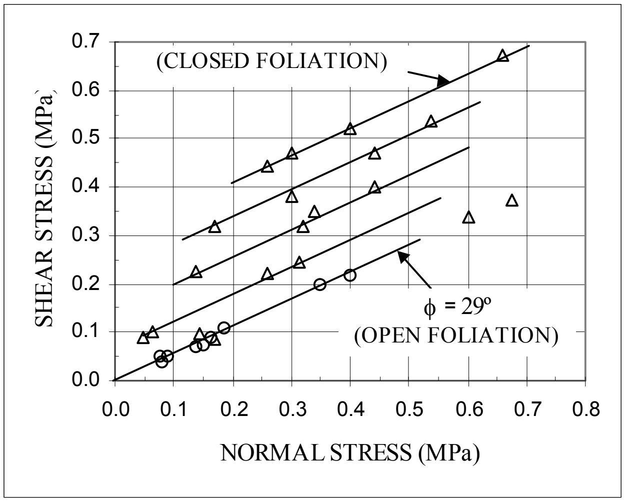

Figure 7. Straight lines fitted to peak closed foliation results, parallel to open foliation envelope.

4.2 Ultimate strength

Values of shear stress versus normal stress for peak behavior of open foliation specimens and the post peak behavior of open and closed foliation specimens are shown in Figure 8. It can be seen that a lower bound linear envelope will show zero cohesion and a 12º angle which was considered as the ultimate angle of internal friction (ϕu). The ultimate values of all specimens tested varied from 12º to 23º.

The maximum linear envelope that can be fitted in Figure 8 shows an angle of 29º up to a normal stress of 0.4 MPa. After that value, (with the exception of two points suggesting that the 29º envelope continues with the same slope), there seems to be a tendency for a drop in the friction angle down to 19º. This behavior agrees with Patton (1966) bilinear envelope for open joints. The upper envelope in Figure 8 has been drawn bilinear as an approximation but as Patton (1966) noted, the true mode of failure would tend to be curved reflecting not a simple change but changes in the intensities of different modes of failure occurring simultaneously.

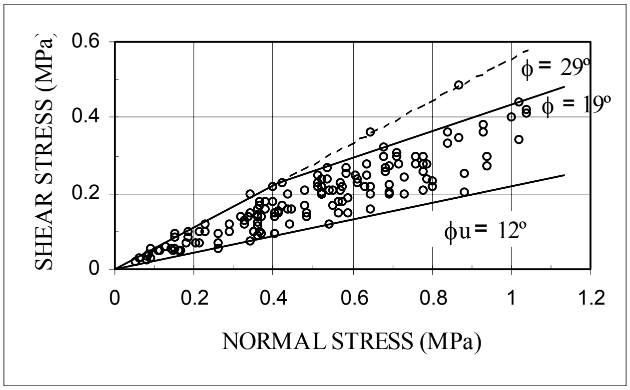

Figure 8. Peak strength results of open foliation specimens and post-peak results of open and closed foliation specimens.

4.3 Roughness profiles and differences between peak and ultimate strength

According to roughness profiles of foliation surfaces determined in laboratory samples of phyllites by means of a contour gage, it may be stated that at the scale of samples the open foliation surfaces are very smooth and nearly planar with an estimated peak dilation angle ranging from zero to a maximum of 5º.

Based on Barton & Choubey (1977), a joint roughness coefficient equals or less than 5 (JRC ≤ 5) describes the roughness characteristics of the phyllites tested. Figure 9 shows typical roughness profile of a phyllite sample, measured by a contour gage.

Results of shear tests revealed that the difference between the peak strength (ϕp) and the ultimate strength (ϕu) for samples with open foliation surfaces varied from 6º to 17º. According to open joint theories the difference between the peak friction angle and ultimate friction angle corresponds to roughness angles (i) at low normal stress. However, calculated high "i" angles do not correlate with the smooth and nearly planar roughness profiles determined on the samples tested. In this way a new mechanism different than overriding of original asperities must be proposed to explain the large difference between ϕp and ϕu.

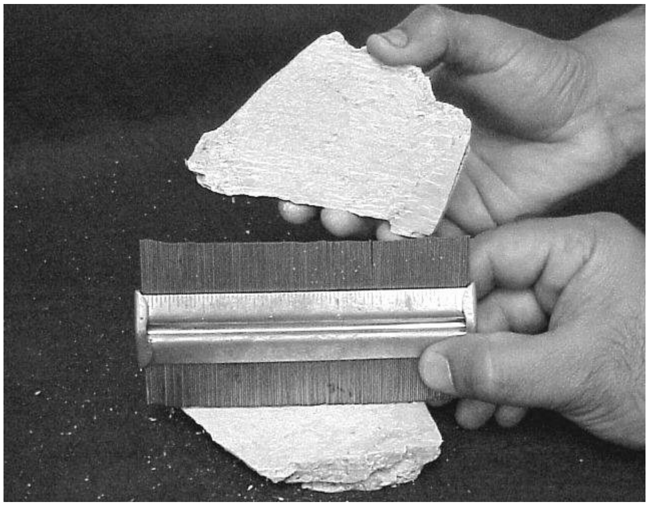

Figure 9. Typical planar and smooth roughness profile of phyllites tested.

4.4 *Proposed failure mechanism*

Due to the aforementioned incongruities of results, some tests were stopped before reaching the peak value in order carefully to observe the foliation surface subjected to shearing. It was observed that the original smooth surface developed a stepped profile during the shearing process. The writer believes that due to the fact that the weathered rock is weak and the foliation surfaces are so closely spaced, the rocks breaks in tension in some areas during shear. These fractures, which are approximately normal to the mean shear plane, seem to develop along the incipient crenulation cleavage observed in the samples tested. During this process a sort of a random profile, passing from one foliation surface to another, is developed. The effect of the developed stepped profile is to increase the peak friction angle due mainly to dilatancy at low normal stress.

It is also possible that due to the weakness of the phyllite tested, at low normal stresses some irregularities are sheared off. It can also be explained that in the range of high normal stresses (>0.4 MPa, Figure 8) the same mechanism originating the stepped shear surface takes place. However, the mechanism of failure involves mainly shearing through the steps and the original small asperities. Under this condition the valid Mohr-Coulomb failure criterion could be expressed in terms of the cohesion and the friction angle of the rock material.

Finally it has to be explained that the stepped profile tends to disappear after the peak because, at large displacements, the rock pieces resulting from initial breaking of the rock tend to fill the spaces between foliation surfaces, developing a gouge with a nearly smooth surface where the ultimate friction angle is obtained.

5 CONCLUSIONS

1. Use of the same technical terminology related to shearing behavior of different discontinuities, is necessary to share knowledge about this topic.
2. Field characterization of metamorphic rockmasses, mainly in those areas where they have been subjected to various generations of superimposed foldings, must be accomplished by an expert geologist with a rock engineering background. Involuntary field mistakes may lead to erroneous geotechnical models and as a consequence, results of slope stability analysis may be far from reality.
3. It has to be expected that peak strength results obtained from direct shear test along closed foliation surfaces, will have a considerable amount of dispersion. Thus, results can not be interpreted in terms of Mohr-Coulomb theory due to the fact that samples tested may have a different proportion of penetrative and non-penetrative areas in the foliation plane.
4. Shear test results along open foliation surfaces of weathered phyllites show significant differences between peak and ultimate friction angle, which do not correspond to the typical planar smooth surfaces of the rock tested. In this sense a failure mechanism has been proposed to explain this non-typical behavior.
5. Further research is needed to study the influence of crenulation cleavage on the failure mechanism of foliation surfaces. A series of direct shear tests along foliation surfaces, varying the direction of applied shear force with respect to orientation of crenulation cleavage, must be performed to investigate this particular shear behavior.
6. The influence on shear behavior of other kinds of cleavage and typical features that characterize some metamorphic rocks, must also be investigated. Careful observation and description of structures present in rock samples are absolutely necessary before performing shear tests, in order to understand shear behavior. This line of rock mechanics research requires additional participation of experts in structural geology.

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