Characterization of Phyllitic and Schistose Rock Masses: from System Behaviour to Key Parameters

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ABSTRACT: Phyllitic and schistose rock masses have a wide range in behaviours during tunneling. The changes in displacement characteristics are related to the spatial distribution of the foliation and major geologic structures in the vicinity of the excavation. Direct shear tests were used to quantify the anisotropic shear strength of phyllites and identify failure mechanisms at the sample scale. It was found that these observations were also valid for evaluating the rock mass response during tunneling.

1 INTRODUCTION

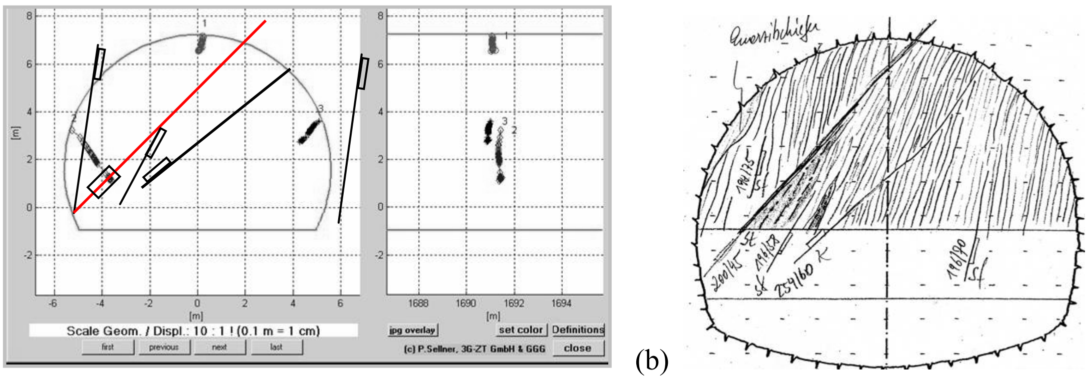
Rock mass characterization is the first and most important step in developing an engineering design for underground excavations. Within this step the geological model is subdivided into similar regions or homogeneous sections, most often based on similar lithology and rock mass structure. Many of the procedures available to the geotechnical engineer that assist in this process utilize limited number physical and spatial parameters that are universally applied to all rock mass types. Intact rock properties typically include the deformability and strength, while discontinuity properties such as orientation, spacing, infilling, and persistence are usually considered. How these characteristics are combined to classify the rock mass depends on the system applied. The end result of these systems is a rating value that can be used to compare different rock mass qualities, estimate rock mass deformability and provide a first estimate for support requirements. However, the relationships utilized by these systems to estimate the response to the excavation often homogenize the rock mass into a quasi-continuum based on empirically or numerically derived "equivalent" rock mass properties. In rock masses where anisotropy and or singular features have a large influence on the rock mass response these procedures may not be adequate to develop the optimal excavation and support methods or to give insights for the interpretation of monitoring data.

The goal of the characterization process should be to evaluate the physical characteristics of the rock mass that have the largest influence on the excavation behaviour (i.e. key parameters); this process should be site and rock mass specific, Schubert & Riedmueller (2001). In order to optimize the excavation and support methods during design it is necessary to consider how the rock mass will respond to the excavation without considering support (i.e. rock mass behaviour). Conceptual, analytical, physical, and numerical models can be combined with previous experience to assess potential failure mechanisms, which can then be ranked according to their probability of occurrence. The support should be designed to counteract the potential failure mechanisms, as well as meet any project specific requirements related to environmental impacts. Since the excavation and support is ultimately based on the rock mass behaviour; instead of defining homogenous sections based on physical properties it is more appropriate to define regions of similar behaviour, Schubert (2001). The predicted response of the supported tunnel (i.e. system behaviour) provides a basis for interpreting monitoring results and allows deviations from the expected tunnel behaviour to be identified during construction and the appropriate support adaptations implemented.

Anisotropic rocks such as phyllites and schists are often associated with difficult tunnelling conditions, especially in alpine environments where they are often affected by brittle deformation. The anisotropic behaviour and the influence of the rock mass structure associated with these rock types can not be adequately accounted for in empirical systems that homogenize the rock mass. To identify which rock mass characteristics have the largest influence on the system behaviour; data, consisting of the geologic documentation, tunnel displacements, and support methods were evaluated from several tunnels recently constructed in these rock types. To evaluate the local strength characteristics of these rock types and identify failure mechanisms at the sample scale direct shear tests were performed on intact and jointed samples of different qualities. With these evaluations it was possible to identify characteristic system behaviour and how they related to different rock mass structures.

2 SYSTEM BEHAVIOUR

The influence of the rock mass structure on the excavation response was based on evaluating the measured displacements for consecutive monitoring sections and comparing the changes to the observed changes in geology. The measurements utilized were 3-D absolute displacements made by optical surveying. For evaluating the displacement characteristics and their relationship to the rock mass conditions it is easiest to plot the displacements in cross sections. The examples shown below come from two tunnels in similar rock types (quartz phyllites) but the dominant rock mass structures vary. Figure 1a shows a typical measurement profile, the data was plotted using the evaluation software Geofit®, Sellner (2000), the displacements are magnified and their scale relative to the excavation scale is given. Figure 1b shows the corresponding geologic conditions as documented during the excavation. The main structures are schematically drawn on the displacement graph to highlight their influence. Both the cross section and longitudinal section are shown to allow a 3-D evaluation of the data. The response show in Figure 1 (a) is characteristic for a steeply dipping foliation striking semi-parallel to the tunnel axis as shown in Figure 1 (b). The thin lines represent the foliation, the thick dark line a joint, and the thick lighter line a small fault. Mueller flags are shown to indicate the strike of the structures. The overburden in this region was approximately 500m. The largest displacements typically occur where the foliation is tangent to the excavation boundary while the smallest displacements are typically in the crown.

(a) 

(b)

Figure 1. (a) Monitoring data displayed in cross sections. (b) Geologic documentation

Figure 2 shows the typical behaviour observed in the second tunnel in which the foliation dips slightly in the direction of the excavation, the strike approximately 20° from the tunnel axis. In this section the overburden is approximately 300m. In this rock mass structure the largest displacements occur in the crown, while both sidewalls have a similar displacement magnitude. The large longitudinal displacements in this example result from the influence of a fault zone encountered approximately 40m after this monitoring section as discussed by Steindorfer (1996).

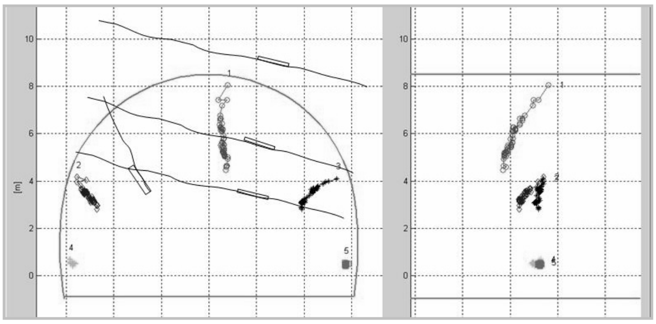


Figure 2. Typical displacement characteristics observed for a foliation dipping in the direction of the excavation and the strike approximately 20° from the axis. Displacements are scaled at 50:1

When the foliation strike changes relative to the tunnel axis, either through folding or changes in the tunnel orientation it was observed that the longitudinal displacements can be influenced due to the change in kinematics associated with movements into the excavation space. Figure 3 shows a typical example of this behaviour. The lower left side point moves against the tunnel direction as its free space is above the foliation plane. The lower right side point moves in the opposite direction with an increase in the longitudinal proportion after about two days. This increase is attributed to the increased kinematic freedom as the excavation passes. This type of response is attributed to dilation normal to the foliation and is amplified when cross joints intersect foliation and diminishes as the foliation strike becomes more perpendicular or parallel to the excavation (reduction in kinematic freedom). The displacements at the lowest monitoring points are associated with the bench excavation and are not comparable to the other points.

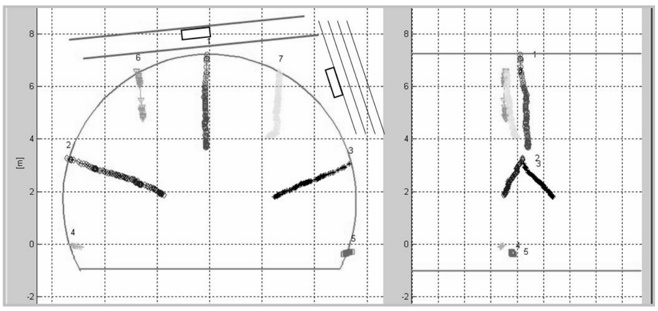
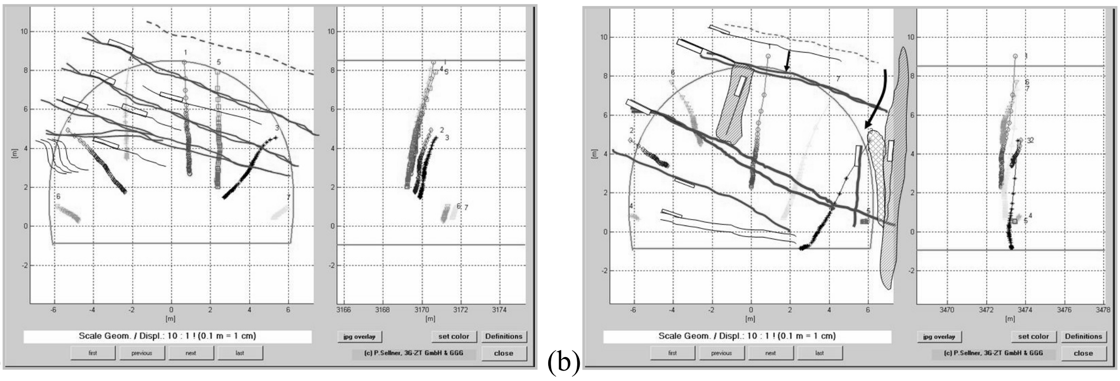


Figure 3. Behaviour influenced by an oblique foliation, Displacements are scaled at 10:1.

It is very common in foliated rocks to have brittle shear zones parallel to the foliation. In these cases it has been observed that the displacement pattern remains very similar to the standard case while the displacement magnitude increases due to the decrease in rock mass strength and increase in deformability associated with brittle deformation. Figure 4a shows an example from a shallow dipping foliation with multiple foliation parallel shear zones. The displacement pattern is very similar to that shown in figure 2, while the displacements are more then 10 times greater. The largest displacements are at the right spring line and decrease slightly towards the left spring line. This is attributed to the slightly oblique strike and shallow dip of the rock mass structures.

In addition to foliation parallel shear zones it is also common to encounter shear zones at high angles to the foliation. These features can have a significant impact on the observed system behaviour. In addition to further decreasing the rock mass quality, they introduce additional kinematic freedom, create large blocks bounded by sheared material and have a large influence on the stress redistribution around the excavation. Figure 4b shows how both the displacement pattern and magnitude becomes highly anisotropic when these features are located in the immediate vicinity of the excavation. Their spatial relationship to the excavation governs the behaviour.



(a) (b)

Figure 4. Behaviour influenced by both foliation shears and high angle shear zones

Two shear zones are at high angles to the foliation shears in this example, one is locally confined between two shears in the central zone of the excavation while the other is located just outside of the right excavation boundary. In this case the behaviour indicates that the rock mass above the right half of the excavation shears along the steep shear as indicated by the arrow. The displacements decrease towards the left side of the excavation with the smallest displacement occurring in the left side wall indicating rotation or very heterogeneous internal deformation. Again the largest displacement is observed in the right spring line.

3 LABORATORY BEHAVIOUR

Analyses of the monitoring data indicate that the foliation plays a critical role in the rock mass response. Considerable information is available on the compressive strength of these materials including Ramamurthy (1993), Behrestaghi (1996), Nasseri (2003), however, there is very little published information on the shear behaviour of these rock types. A program was carried out utilizing advanced servo-controlled test procedures as described by Blümel & Bezat (1999), Blümel, Button & Pötsch (2002), to evaluate how the shear strength varies with orientation and what failure mechanisms dominate in different stages of the shearing process. The shear displacement was typically 25mm unless the normal load dropped below the weight of the upper shear box at which point the test had to be stopped.

3.1 *Shear Strength Anisotropy*

In order to assess the anisotropic shear strength of good quality phyllitic rocks a total of 12 shear tests were performed with the foliation orientated at different angles relative to the shear direction. Five tests were performed with the foliation parallel to sub-parallel to the shear direction (PS series), three tests were conducted with the foliation approximately at 85° against the shear direction (NS series), and four tests were conducted with the foliation at different orientations +/- 20° and +/- 30° to the foliation (IS series). The test procedure was the same for all of the tests and used displacement controlled boundary conditions, the normal displacement was held constant after consolidation and a constant shear displacement rate was used, typically 0.05 to 0.2 mm/min depending on the loading direction. Table 1 summarizes the results for this test series. The residual friction and cohesion are listed in the first column; a peak friction angle is not given since the initial failure is associated with the initial shear plane development. The maximum shear stress and maximum normal stress and their associated displacements are given as well as the traction (normalized by the sample area) and its orientation to the shear direction. In most cases the shear stress was larger then the normal stress at the initial failure indicating a tensile stress state within the sample, this magnitude and the associated displacement are given in the last columns.

There are two ways to assess the anisotropic strength ratio in this case, one is the initial maximum shear stress, which has a range from 2.28 MPa to 11.46 MPa, and the other is looking at the dilation potential through the maximum normal stress, which has a range of 1.53 MPa to 37.08 MPa. These results indicate that the shearing resistance of these materials varies considerably with orientation.

Test	ϕ_r	c_r (MPa)	τ_{max} (MPa)	Disp.(mm) τ_{max}	σ_{n_max} (MPa)	Disp. (mm) σ_{n_max}	$Tr_{\_max}$ (MPA)	$Tr_{\_orien.}$	Disp. (mm) SV	σ_t (MPa)	Disp. (mm) σ_t
PS_1 *	21° -30°	0,08	2,28	0,5	3,63	3,53	4,1	30,8°	3,6		
PS_1 ini.			2,28	0,5	1,68	0,5	2,83	57°	0,5	-0,757	0,43
PS_2	28°	0,016	3,33	0,66	4,1	1,52	4,75	43,7°	0,68		
PS_2 ini			2,34	0,11	1,84	0,11	2,98	52°	0,11	-0,5	0,11
PS_3*	31°	0,388	5,08	0,6	4,48	19,4	5,8	61°	0,6		
PS_3 ini			5,08	0,6	2,81	0,6	5,8	61°	0,6	-2,26	0,6
PS_4	26°	0,375	2,94	0,2	5,28	3,83	5,9	27,1°	3,83		
PS_4 ini			2,94	0,2	1,53	0,2	3,32	62°	0,2	-1,44	0,19
PS_5	25°	0,66	2,62	9,49	5,14	9,96	5,72	27,4°	9,78		
PS_5_ini			2,52	0,26	1,66	0,31	2,99	56,7°	0,28	-0,95	0,24
IS_-20°	28°	0	5,18	0,46	3,19	0,47	6,08	58,4°	0,47	-2	0,46
IS_+20°	25°	3,32	13,2	9,38	20,99	9,61	24,5	31°	9,57		
IS_+20° ini			6,8	0,46	3,74	0,46	7,76	61,2°	0,46	-3,06	0,46
IS_-30°	22°	0,06	5,57	0,376	3,85	0,38	6,76	55,4°	0,376	-1,8	0,29
IS_+30°	31°	0,216	7,4	1,28	8,98	5,78	10,86	34,1°	5,78		
IS_+30° ini			7,4	1,28	3,5	1,28	8,18	64,7°	1,28	-3,97	1,24
NS_1	22°	0,19	7,47	3,17	16,4	5,17	10,63	21,7°	5,79	-1,33	1,06
NS_2	24°	0,3	11,46	4,06	37,08	5,38	48,04	26,2°	4,9	n.a	n.a.
NS_3	31°	0	11,06	2,55	26,52	3,93	28,3	20,5°	3,92	n.a	n.a.

Table 1. Summary of the test results, the shaded lines indicate the stress conditions at the first failure of the sample if it does not coincide with both the maximum shear and normal stress.

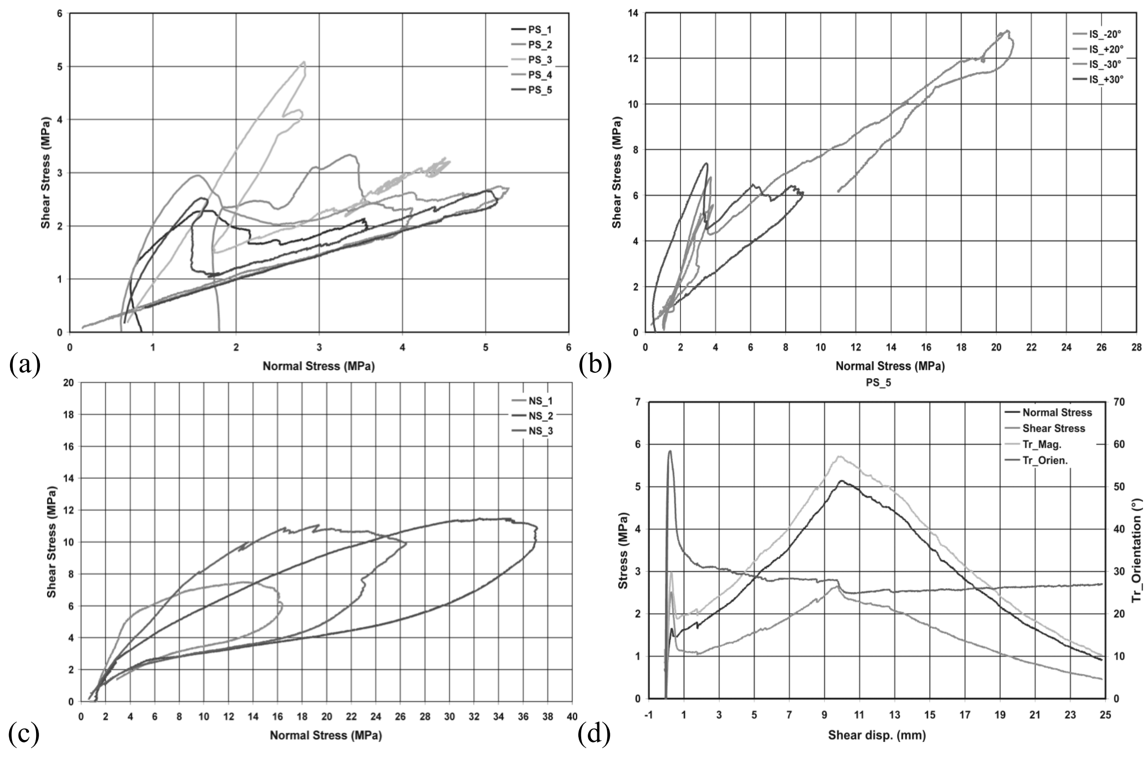


Figure 6. Stress paths for the discussed test series (a) parallel shear (b) inclined shear (c) normal shear (d) stress-displacement diagram for PS-5 including the traction magnitude and orientation

Figure six shows the stress paths for this test series. The tests are grouped into three categories, parallel shearing, inclined shearing, and normal shearing. It can be seen that within any one group that the behaviour was quite similar and the residual strength relationships were almost identical while the peak strengths varied considerably. Figure 6d shows the stress displacement diagram as well as the traction magnitude and orientation for test PS-5. The traction orientation is similar to an instantaneous friction cone analysis for a sliding block. The initial failure occurs at a very low displacement and is followed by a shear stress drop while the normal stress continues to increase, then with continued displacement both the shear and normal stress increase due to the samples tendency to dilate, which is restricted with this test procedure, and the mobilization of the frictional strength. When a shear plane is formed that does not dilate both stresses decrease along a residual strength envelope.

Observations both during and after the tests indicate that the initial failure of intact phyllites is dominated by tensile failure of the foliation planes, with continued shear displacements friction is mobilized along individual foliation planes and in zones with dilation due to the foliation morphology tensile fractures occur through more competent layers, such as quartz. With this process the frictional strength is derived almost uniquely by the shearing of phyllosilicate layers. As the shear direction deviates from the foliation orientation more damage occurs due to the cross layer fracturing and a gouge material develops. The wide range of peak strengths is related to the fracture propagation characteristics associated with different proportions of fracturing along phyllosilicate layers and cross fracturing through more competent materials. As the foliation orientation deviates from the shear direction more cross fracturing is required to form a shear plane thus more energy and higher stresses are required.

4 SUMMARY

Direct shear tests allowed the anisotropic shear strength of foliated samples to be quantified. The wide ranges of peak strengths was attributed to different tensile fracture propagation characteristics associated with the weak phyllosilicates and more competent mineral layers. Combining the results from the laboratory and case history evaluations indicates that when characterizing phyllitic and schistose rock masses key parameters include: the foliation type, persistence, strength, and relative orientation; the strength, deformability, orientation, and spatial distribution of fault zones. For a given rock mass structure there is a characteristic displacement pattern, changes in rock mass quality result in an increase or decrease of the displacement magnitude at the same stress levels. Singular structures, such as shear zones, when oblique to the foliation result in changes to the displacement pattern and usually result in highly anisotropic displacements.

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