Parameters Influencing the Shear Behaviour of Clay Infilled Rock Joints

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Abstract

The rock masses are heterogeneous and contain discontinuities. The discontinuities existing in rock masses are normally filled with fine material such as clay. The presence of clay infill in discontinuities has a major influence on the stability of rock mass.

The shear behaviour of infilled joints is significantly controlled by several parameters such as the type of joint and infill material, surface roughness and thickness of infill, drainage condition, the degree of overconsolidation etc. It is expected that the difference in shear strength between normally and overconsolidated states may be very large and the degree of overconsolidation of clay infill probably exceeds even the most overconsolidated deposits. Furthermore, a real danger is in the underestimation of pore pressure change, softening, and swelling. Therefore, the effects of pore pressure and the degree of overconsolidation on clay filled rock joints are analysed carefully with proper laboratory simulation.

Introduction

The shear strength of rocks and rock joints plays a key role in the field of Civil Engineering and Geo-sciences. Generally, rock masses contain discontinuities in the form of joints, faults and other such features with varying degrees of strength along their plane of weakness. The presence of discontinuities in rock masses not only decreases the shear strength, but also makes it more deformable and more permeable.

In nature, the discontinuities existing in rock masses are normally filled with foreign material. The choice of correct shear strength parameters becomes more difficult for joints in hard rocks, if they get filled with weak or loose material. These infill materials found in rock joints may be related to the origin of fracture itself with subsequent tectonic action or related to environmental conditions (e.g. infill material transported by water).

The typical infill material existing within joint interfaces can be divided into the following four categories ([1] Lama):

- Loose material brought from the surface such as sand, clay etc.,
- Deposition by ground water flow containing products of leaching of calcareous or ferruginous rocks,
- Loose materials from tectonically crushed rock, and
- Products of decomposition and weathering of joints.

The joint infill may exist in the form of partially loose to completely loose cohesive or non-cohesive materials under fully saturated or partially saturated condition. Any clay infill in a sloping discontinuity makes rock masses more slippery when it becomes wet and thereby promotes failure. Thus, the presence of clay infill in discontinuities has a major influence on the stability of rock mass. The thickness of infill may vary from few microns to several meters. An increasing degree of complexity is introduced into the problem, when the thickness of clay infill is approximately less than the roughness amplitude of the joints.

Various research studies have been conducted in the past under different test conditions to investigate the shear behaviour of infilled rock joints. Those studies report that the shear behaviour is significantly controlled by several parameters such as joint type, the roughness of joint wall, thickness of the infill, stress history and pore water pressure.

Research on infilled rock joints

The majority of research on infilled rock joints has been empirical. Systematic research has been conducted under drained condition using direct shear tests (Constant Normal Load condition (CNL) and Constant Normal Stiffness condition (CNS)) to study the effect of surface roughness, different kinds of infill material, thickness of infill etc. on the behaviour of infilled rock joints. However, limited studies have been carried out on infilled joints under undrained condition, and no systematic research has been executed to model the overconsolidation effect.

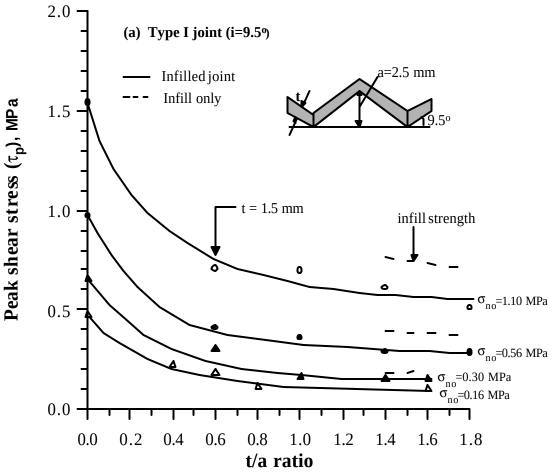
Factors affecting the infilled rock joint behaviour

1. Type of joint and infill material

The shear behaviour of infilled joints is significantly influenced by the properties of rock joint such as compressive strength of rock and rock joint, roughness amplitude of joint wall, the degree of weathering etc. and the type of infill material (eg. different types of clay, silt, sand etc.). In the past, laboratory tests have been conducted on natural joints and model joints such as concrete bricks and gypsum plaster bricks to investigate the effect of infill and thickness on the shear behaviour of infilled joints ([2] Indraratna et al., [4] Toledo & Freitas, [1] Lama, [7] Ladanyi & Archambault, [8] Kanji). Since it was impossible to use natural joints for systematic repetitive testing, model joints were produced precisely to match the same geometry and without much variation in the material properties. Their results vary with the type of joints and infill material. It is expected that some complication arises due to the infill that consists of widely graded material, for instance rock breccia down to clay.

2. Joint surface roughness and thickness of infill material

The infill thickness (t) and surface roughness amplitude (a) are the most important parameters controlling the shear strength of infilled joints. Several investigations have revealed the shear strength of infilled joint reduces with increasing infill thickness and eventually reaches to a value, approximately equal to the shear strength of infill alone at a critical (t/a) ratio (([2] Indraratna et al., [4] Toledo & de Freitas, [5] Papliangas et al., [6] Phien-wej et al., [1] Lama, [7] Ladanyi & Archambault, [8] Kanji, [9] Goodman). This critical (t/a) ratio varies with the type of joints as well as the type of infill material. Some critical (t/a) values for infill from test results are shown in table 1. Indraratna and Haque [3] have performed the tests under Constant Normal Stiffness (CNS) condition for bentonite clay filled joints. Figure 1 and Figure 2 illustrate the effect of infill thickness and surface roughness on the shear behaviour of the joints.



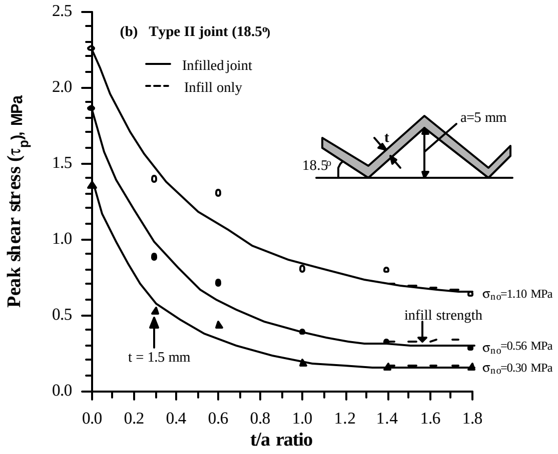


Figure 1. The variation of Peak shear strength with t/a ratio, for the type I and type II joints, (Indraratna and Haque, [3])

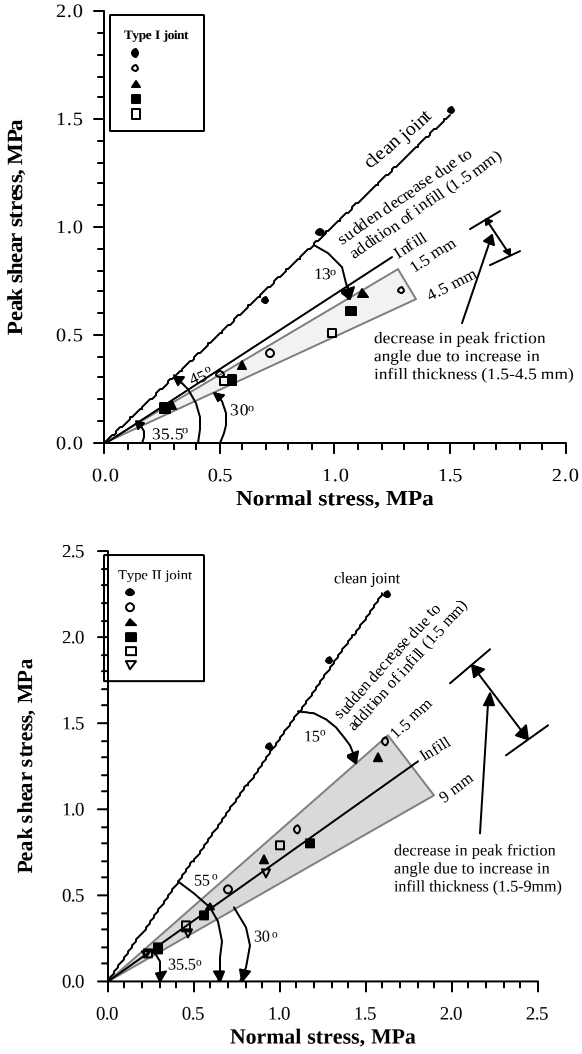


Figure 2. The effect of infill on the shear behaviour of rock joints, (Indraratna and Haque, [3])

Table 1. The Critical (t/a) ratio for different types of infill material and model rocks

Researchers	Type of model rock	Type of infill	Critical (t/a) ratio
Indraratna et al., [2]	Saw-toothed gypsum plaster block	Bentonite clay	1.4
Toledo and Freitas, [4]	Toothed Penrith sandstone	Clay	1
Papaliangas et al., [5]	Toothed, plaster cement bricks	Kaolin	0.6
		Fuel ash	1.25-1.5
Phien-wej et al., [6]	Toothed gypsum bricks	Dried bentonite	2
Ladanyi and Archmbault, [7]	Toothed concrete bricks	Kaolin clay	1
Goodman, [9]	Plaster-celite cast toothed joints	Crushed mica	1.25

3. Drainage condition, strain rate and pore water pressure

Drained or undrained tests are employed for effective stress or total stress analysis respectively. In all testing, the aim is to simulate the field conditions as closely as possible. The undrained shear strength of normally consolidated clay is always less than that of drained shears strength. But the undrained shear strength of overconsolidated clay may be smaller or larger than the drained strength depending on the value of overconsolidation ratio. For lightly overconsolidated clay, the volume tends to decrease during shear and undrained shear strength is less than the drained strength. However for higher values of the overconsolidation ratio, the clay tends to increase in volume during shear, the pore pressure correspondingly decreases and the undrained strength exceeds the drained value. The strong negative pore pressure associated with unloading would tend to draw water into the discontinuity causing the infill to soften and swell, whereupon the shear strength would steadily be reduced ([10] Barton).

Research has been carried out ([4] Toledo & Freits) on clay infilled joint at different strain rate under direct shear test condition. They concluded that the slower strain rate represents the drained condition whereas the faster represents the undrained condition (Figure 3).

As discussed by Lane [11], pore water pressure changes are sometimes critical to the safety of the engineering works on rocks, e.g. all kinds of dams, navigation locks, power houses, spillway excavation etc. Several important failures of hydraulic structures and of natural slopes have been attributed mainly to the action of water pressure inside the rocks and rock joints. Yet, experimental data on induced pore pressure on rock sample with joints and infilled joints are very scarce. The authors believe that this does not originate from the lack of appreciation of the problem importance but the difficulties in carrying out such elaborate experiments.

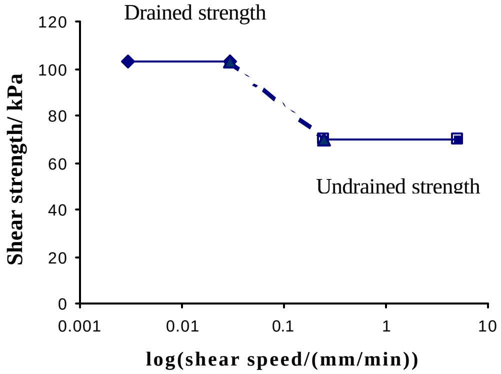


Figure 3. The effect of rate of shear on clay infilled rock joints (Toledo & Freits, [4])

4. The degree of overconsolidation

In soil mechanics, the deposition-consolidation-erosion cycle which gives rise to overconsolidated clay is universally recognised, and the consequences are far reaching. The following discussion is directed towards the possible effects of overconsolidation on both infilled and unfilled joints intersecting the rock.

Increase in the shear strength of unfilled joints due to over-closure, an overconsolidation effect

In nature, the unfilled joints are never entirely closed and the degree of closure depends on the normal stress acting on them. It is possible for non-planar joints (particularly tension joints) to become mechanically over-closed. The shear strength of preloaded tension joints was found to be considerably higher than that of normally loaded joints ([12] Barton).

Barton [12] has investigated this effect on the natural rock joints using shear testing. Those samples were preloaded before shear testing under the lower engineering normal stress levels. However, the effective preconsolidation pressure, p_c, representing the undisturbed closure condition would not be known exactly. In an engineering approach to this problem, the historical preconsolidation pressure, p_c, had to be ignored and the problem simplified to an estimation of the ratio of overconsolidation caused by the progression from "undisturbed" to "post construction", for instance in slope excavation. Here the post construction stress will be less than the undisturbed in situ stress, hence the overconsolidation effect. This degree of overconsolidation produced a significant over-closure effect in rough, unweathered model tension joints, which was reflected by a significant increase in the stability of the slopes between the two cases.

A set of preconsolidated direct shear tests performed by Barton [12], on model tension joints clearly demonstrates the potential increase in shear strength due to the overconsolidation effect. The tests have been performed for the overconsolidation ratios of 1, 4 and 8 as shown.

(1) s_n (Preconsolidation) / s_n (test) = 8/1

(2) s_n (Preconsolidation) / s_n (test) = 4/1

(3) Normally loaded (1/1)

The test results show (Figure.4), there is an increase in friction angle of approximately 5° and 10°, when the model overconsolidation ratios are increased from 1 to 4, and from 1 to 8 respectively. Furthermore, Barton [12] concluded that the increased closure of the joints caused by high overconsolidation ratios necessitated larger dilation angles for the peak strength to be reached.

The effect of overconsolidation ratio on infilled joints

The infilled joints are overconsolidated, if the present stress is less than the preconsolidation pressure. It is probable that almost all discontinuities, filled or unfilled are in an overconsolidated state when exposed at the surface. There may be an additional overconsolidation effect between the stages “undisturbed” and “post construction”, since the undisturbed in situ effective normal stress may exceed the post construction effective normal stress particularly in the case of slope excavation.

The residual strength will be almost independent of the history of loading of the discontinuity. However, the history of loading has an enormous influence on the peak strength of infilled joints. Overconsolidated clay shows a marked difference in shear strength parameters between peak and residual due to reorientation of clay particles within narrow bands next to the shear surface. Furthermore, the dilation, accompanying shear in overconsolidated clay allows an increase in water content and consequent softening to occur ([10] Barton). The filled joints are classified as recently displaced joints and undisplaced joints to explain the importance of the overconsolidation effect on infilled joint.

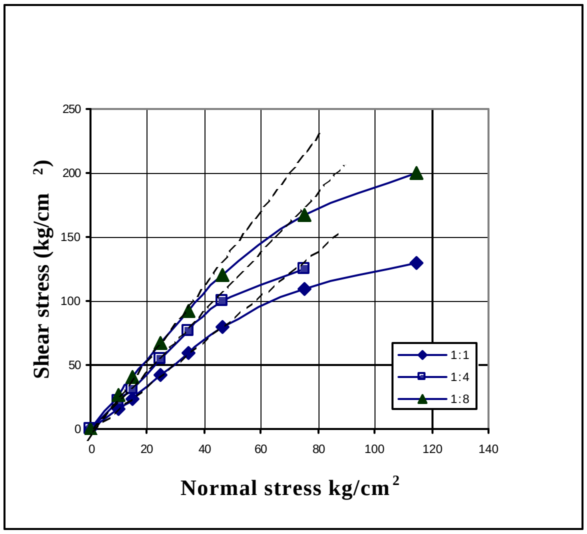


Figure 4. The effect of over-closure on unfilled joint, an overconsolidation effect (Barton [12])

In the case of recently displaced infilled joints such as shear zone and bedding plane slip, the shear strength will be close to the residual shear strength Therefore, whether normally consolidated or overconsolidated is not of great importance. But, in the case of undisplaced infilled joints such as interbedded clay bands and hydrothermally altered fillings, the shear strength will be close to the peak shear strength. Therefore, it is important to consider the infill whether normally consolidated or overconsolidated to accurately analyse the behaviour ([10] Barton).

The influence of stress history, or paleo-overburden stress, on the shear strength of the clay-limestone contact was studied by subjecting the contact to confining pressures greater than the current *in situ* vertical stress ([13] Hatzor and Levin).

It has been shown that the paleo-overburden influences the frictional resistance of clay–limestone contact, from the test results of precompressed samples in conventional triaxial tests. Their test results justify that in the analysis of rock slope stability of clay filled discontinuities, the influence of paleo-overburden stress on frictional resistance must be resolved before the appropriate constitutive laws can be established for analysis.

Recent model on infilled rock joints

The effect of infill on the shear strength drop of rock joint is generally recognised ([7] Ladanyi and Archmbault, [5] Papliangas et al). Recently, Indraratna and Haque [3] have predicted the strength drop (?t_p) (Figure 5) associated with infill thickness, relative to peak shear strength of clean joint using hyperbolic modelling. The tests have been carried out under constant Normal stiffness condition.

$$(t_{p})_{\inf illed}=(t_{p})_{unfilled}-\Delta t_{p}$$

Here, $(t_{p})_{unfilled}$ has been modelled using energy balance concept, incorporating the Fourier series.

And, the strength drop $(\Delta t_{p})=s_{no}\left(\frac{t/a}{a\times t/a+b}\right)$

s_{no} -Initial normal stress
a, ß- Constants (Figure 6)

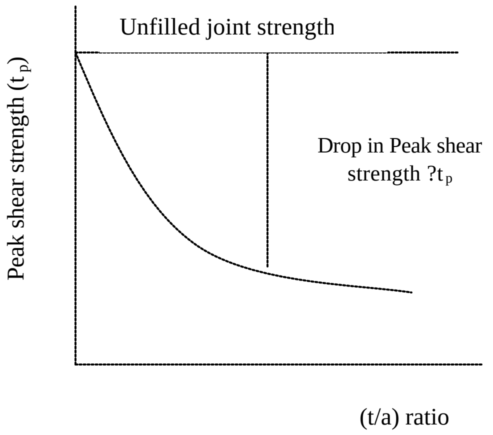


Figure 5. Peak shear strength drop due to infill, (Indraratna and Haque, [3])

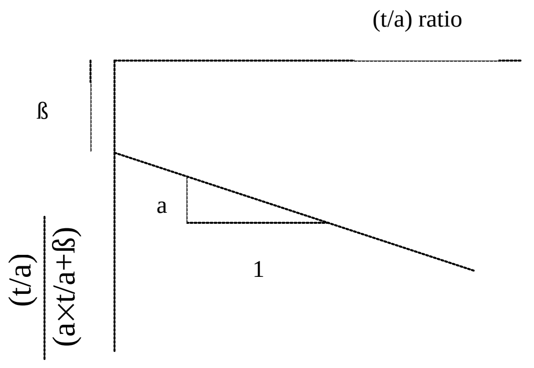


Figure 6. Formulation of hyperbolic model for the drop in peak shear strength due to infill, (Indraratna and Haque, [3])

Future research

In the past, most researchers have studied the behaviour of infilled rock joints using direct shear test condition without really simulating the actual stress path. Furthermore, tests on unconfined rock specimen were found to give incomplete explanation of rock behaviour in situ. In addition, some of the most important aspects of the problem that need to be investigated clearly, are the effect of overconsolidation and pore water pressure development on shear and deformational characteristics of infilled joints. These effects cannot be monitored accurately in Direct Shear test condition

Therefore, the authors undertake this study with the main purpose of systematically investigating the above effects on the shear behaviour of clay infilled rock joints under triaxial condition.

Proposed experimental program

For this research program, carrying out triaxial tests using High Pressure Triaxial Apparatus (HPTA) at the University of Wollongong is recognised. Series of triaxial tests are carried out under Consolidated Undrained (CU) test condition to study the above effects. Since repetitive tests are to be conducted, model rock joints are cast. In this study, the effect of roughness and the thickness of infill are also analysed under triaxial condition. The infill material for the investigation is collected from a rockslide site at Kangaroo valley, NSW.

Analysis on infill material

The infill material collected from the site was stiff clay with the natural water content of between 14% and 16%, and the dry unit weight 18.16 kNm^{-3}. X-ray diffraction analysis of the collected clay revealed that it has 50.5% illite, 39.5% kaolin and 8.8% quartz. The Engineering Classification of the clay is Clay of Low plasticity (CL) with Liquid Limit (LL) 32-39% and Plastic Limit (PL) 21-22%.

Conclusion

The presence of infill significantly reduces the shear strength of joint, resulting in the reduced stability of entire rock mass. The shear behaviour of infilled rock joint is significantly controlled by several parameters such as roughness of the joint wall, thickness of infill, stress history, pore water pressure etc. The (t/a) ratio is used as an important parameter in the prediction of shear behaviour in most research. Any (t/a) ratio greater than the critical (t/a) ratio, the point at which the shear strength of the joint is at lowest value (in most cases, equal to the shear strength of infill alone), the infilled joint behaviour can be largely understood from well tested soil mechanics principal.

It is found that the pore water pressure effect is critical in the design of infilled rock joint. Moreover, it is recognized that there is a considerable difference in shear behaviour between normally consolidated and overconsolidated infilled rock joints. But no systematic research has been executed to analyse and model the above effects on infilled rock joint.

Therefore, a detailed study incorporating the above aspects of pore water pressure and overconsolidation effect is considered important for the better understanding of infilled rock joint behaviour.

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