Shear Behaviour of Infilled Rock Joints Related to Partially Saturated Infill Conditions

W. Premadasa
Department of Civil Engineering, General Sir John KotelawalaDefence University, Sri Lanka

B. Indraratna
School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia

ABSTRACT: Discontinuities such as fault planes, joints and bedding planes have a great influence on the shear strength of a rock mass. These discontinuities may be filled with different types of sediments that are either transported or appear as a result of weathering or joint shearing. The degree to which the infill has been saturated is a governing parameter of the strength of the filled joint, and can vary considerably depending on the climate and groundwater transport patterns. Due to the lack of experimental data quantifying the strength of a joint when partially saturated, it is impossible to predict the shear strength in such instances. A series of laboratory undrainedtriaxial tests on idealised model joints were carried out at constant moisture contents. The experimental results indicate a variation in shear strength for ratios of different infill thickness to asperity height of the filled joint when the infill saturation varied from dry to almost saturated conditions.

1 INTRODUCTION

Rock masses present in nature are generally characterised by discontinuities such as joints, fractures, and other planes of weakness. Discontinuities that are infilled with fine-grained material which is either transported or appears as a result of weathering or joint shearing, will adversely affect the behaviour of the rock mass. These fine infill materials may drastically reduce the shear strength of the rock joints compared to an unfilled or clean joint, because they may prevent the walls of the joint from coming into contact during shear.

The degree of infill saturation is a governing parameter of the shear strength of a filled joint, and it can vary noticeably, depending on the groundwater and climate patterns. For adverse climatic conditions, i.e. heavy precipitation and long periods of rainfall, Barton (1974) reported that the joints act as conduits for water, leaving the fine infill material basically in near saturated conditions. Laboratory testing of infill materials from a rock mass failure site at Kangaroo Valley, New South Wales, Australia, confirmed that the soil can reach more than 95% of saturation after a period of heavy rainfall. During dry seasons the infill saturation will gradually decrease, increasing the shear strength of the jointed rock mass. While studies have been carried out to investigate the behaviour of infilled rock joints (e.g., Ladanyi &Archambault 1977; Lama 1978; de Toledo &de Freitas 1993; Indraratna *et al*. 2005, 2008, 2010), the majority considered either a fully saturated infill condition or a specific level of saturation, thus neglecting the effect of infill saturation. From a practical perspective, most infill materials will likely be compressed over time and typically remain in an unsaturated state unless the joints are submerged by groundwater, which may happen in the event of groundwater inflows occurring through specific discontinuities. In this instance, the joints may be grouted to prevent the infill materials from reaching full saturation, thus reducing the probability of catastrophic rock slides.

In this study a series of constant water content undrained triaxial tests on idealised models of rock joints has been conducted to investigate the effect of infill saturation on the shear strength of filled joints. Although the shear strength of soil at constant water conditions has been studied in the past (e.g., Thu *et al.*2006, Hamid & Miller 2009), no literature is available on infilled joints tested under unsaturated infill conditions.

2 EXPERIMENTAL PROCEDURE

2.1 *Specimen preparation*

A series of identical joint specimens was required for the laboratory testing program to identify the effect of the infill saturation on the shear strength. Due to simplicity and reproducibility a model material was selected to conveniently simulate similar types of rock available in the field. Indraratna (1990) has proposed the use of hydrated gypsum cement ($CaSO_4.H_2O$ hemihydrates, 98%) to model soft sedimentary rocks. This material is readily available, relatively inexpensive, it can be moulded into any shape when mixed with water, and its long term strength is independent of time once chemical hydration is complete. Moreover, the properties of the material depend on the ratio of the gypsum cement and the water used to mix it. A comprehensive evaluation of the gypsum plaster rock based on dimensionless strength factors is given elsewhere by Indraratna (1990).

2.2 *Preparation of idealised saw-tooth joints*

Profiles of an idealised saw-tooth joint with a dip angle of 60°, an asperity angle of 18°, and 2mm high asperities was selected for repetitive tests. A special mould and the joint profile (Fig.1) was fabricated using acetal plastic which can be machined to any desired shape (Indraratna& Jayanathan 2005). The top and bottom profiles of the specimen were fabricated separately to ensure that the joint was fully mated after assembly. The joint profiles were placed in their respective moulds and a silicon based lubricant was applied over the surface of the joint to prevent gypsum plaster from adhering to the plastic. Gypsum cement was then mixed with water in a ratio of 7:2 by weight and stirred until it became a uniform mixture. It was important to ensure the uniformity of the mixture in order to maintain the same material properties throughout the specimens. This uniform mixture was then poured into the mould which was then vibrated mildly to release any air bubbles trapped in the mixture. Air bubbles can result in small cavities in the specimens which can cause a reduction in strength. The setup was allowed to harden for about 30 minutes and then the specimen (Fig. 1) was removed and cured in an oven at a controlled temperature of 40°- 45° C for two weeks. The sample was 54mm in diameter and when the specimens were fully mated their overall length was 110 mm which maintained a height to diameter ratio of 2.0.

2.3 *Selection of infill material*

In this study a silty clay with a 25% of fine sand and 75% of kaolinite by weight was selected as the infill material. Extensive laboratory soil tests were conducted on the infill to identify its properties. Laboratory cone penetration tests showed a liquid limit (LL) of 39% and a plastic limit (PL) of 20% giving a plasticity index of 19%.

Fig. 1 Simulated joint surface profile of the idealised saw toothed joint

2.4 *Preparation of infilled joints*

Five different initial degrees of infill saturation were considered in this study (i.e. 35%, 50%, 60%, 75%, and 85%). The dry density of the infill was maintained constant throughout the test series to omit the effect of infill density because the soil may behave differently if the density is varied. Static compaction of given weight of the infill was used to maintain such condition.

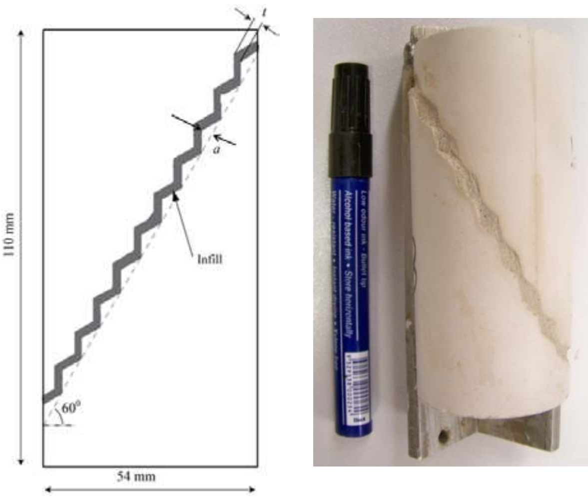

Fig. 2 Idealised saw-toothed infilled joint

Joint specimens were immersed in water for at least 72 hours and then an organic waterproof sealant was applied to the surfaces of the joints to ensure that no moisture escaped from the infill to the specimens during the tests; thus they maintained constant moisture conditions. The infill was mixed in the laboratory to the required moisture content and then spread over the joint profiles with a spatula. Both halves of the joint were assembled and aligned using a scaled "V" block. The sample was then placed into a special cylindrical mould and statically compacted to the required infill thickness to asperity height ratio (*t/a*). An example of the final joint profile obtained once the infill was spread and compacted to a certain *t/a* is shown in Fig.2. Specimens of idealised saw-tooth joints were prepared for a *t/a* of 0.5, 1.0, and 3.0.

2.5 *Testing procedure*

Constant water content triaxial testing (CW) was used to test the infilled joints, and although the test was held under an undrained unsaturated condition, the test procedure shared some similarity to that used in saturated undrained testing. The specimen of unsaturated infill was tested at its initial water content or matric suction, and provided the drainage valves remained closed during testing, constant water conditions were established and undrained conditions were attained. A strain rate of 0.01 millimetres per minute was used for the test series. This shearing rate was consistent with those used in numerous previous studies, including those of Fredlund et al. (2012) and Thu et al. (2006).

The infilled jointed specimen with a known moisture content (or initial degree of saturation) was assembled inside the cell and the confining pressure was applied. Three different confining pressures of 300 kPa, 500 kPa, and 900 kPa were used to investigate the effect of normal stress (or the confining pressure) to shear strength.As noted previously, the waterproofing sealant prevented moisture escaping from the infill to the joint specimen. A series of tests was carried out for different *(t/a)* ratios and with a starting infill saturation of 35%, 50%, 60%, 70% and 85%.

As many as 48 laboratory tests were conducted on idealised saw-tooth joints without repeats. The stress-strain and dilation responses were analysed for each test and the peak shear strength was considered as the maximum shear strength obtained on the stress-strain curve. At the end of each test the moisture content of the infill was measured and compared with the initial value. The difference between the two measurements was typically less than 0.1, which indicates that constant water conditions were attained.

3 RESULTS AND DISCUSSION

The main focus of this study was to investigate the effect of infill saturation on the shear behaviour of infill joints. Fig.3 shows a selected plot of deviator stress against axial strain for varying values of infill thickness and initial degree of saturation for the specimens tested under a confining pressure of 500 kPa for *t/a* ratios varying from 0.5 to 3.0.

When the *t/a* ratios were 0.5 and 1.0, the stress-strain curves showed double peak behaviour. When the joint starts to shear the shear stresses build up rapidly and shear through the infill first, indicating the first peak that corresponds to shearing through the infill. The rock sets the boundary limits for the failure surfaces of the soil, which is defined by the geometry or roughness of the joint. As shearing progresses the infill above the sliding surface must squeeze out to fill the space generated on the unloaded side of the joint. After the infill is squeezed out to the gaps the asperities make contact and the shear behaviour will then be governed by the rock-rock contact or rock strength (Indrarana et al. 2011). The second peak occurs when the asperities are sheared off from the rock walls. In a saw-tooth joint the asperities are regular and have a defined shape, therefore after the tips are sheared off there are no second order asperities to catch up the shear strength. Because of this, a clearly defined second peak could be observed in saw-tooth joints followed by a drop in shear strength. This is a unique characteristic of an idealised saw-tooth joint and has also been reported by Indraratna et al. (2008).

The *t/a* ratio of 0.5 shows a higher peak deviator stresses compared to a *t/a* of 1.0. When the infill thickness is less the effect of the infill material

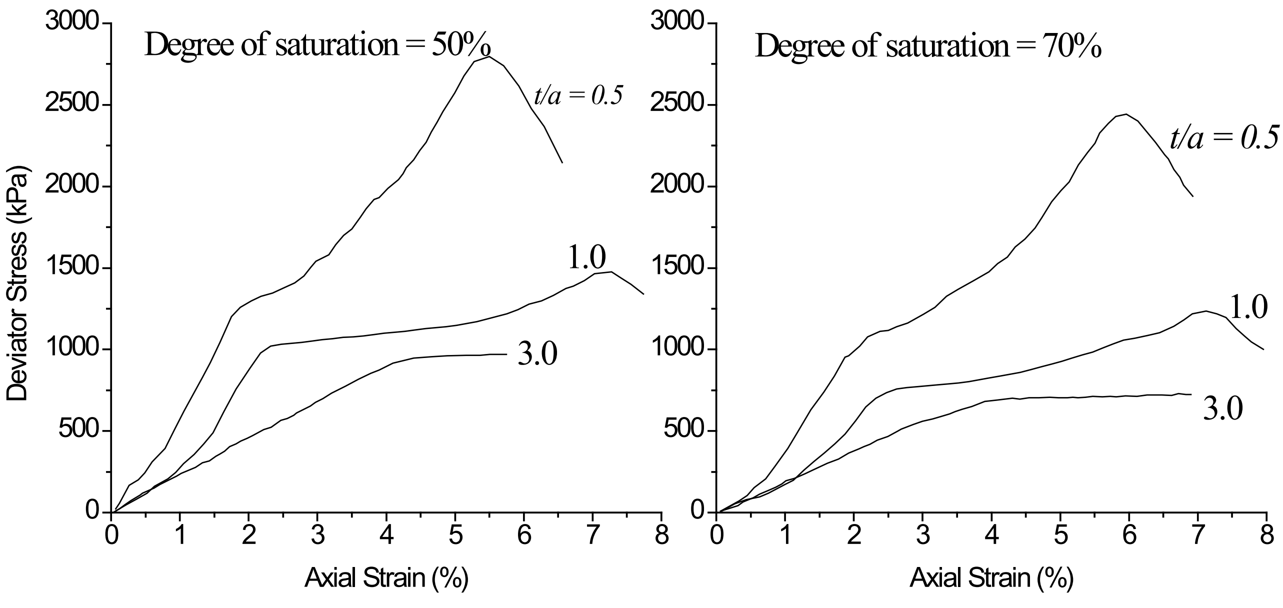

Fig. 3Effect of infill saturation on the shear behavior of infilled saw-tooth joints under 500 kPa of confining pressure is reduced and the contribution of the rock walls and asperities to the shear strength is increased, therefore there were higher peak stresses at lower *t/a* ratios. When the *t/a* ratio increased from 0.5 to 1.0, the axial strain required to attain to peak deviator stress also increased because the larger infill thickness would require more strain to squeeze the infill and to bring the rock walls together. When the *t/a* ratio is relatively high (e.g. 3.0) the joint does not show a clear second peak. The deviator stress gradually increases and obtains a constant value representing the typical shear behaviour of a normally consolidated infill with a little or no asperity interference. This *t/a* ratio define the boundary where the joint acts as infill alone, and is a characteristic of the type of joint and infill.

The peak deviator stress decreased with an increase in the degree of infill saturation. The highest peak deviator stress occurred at 50% infill saturation and was lowest at 85% saturation. Note that the axial strain required to attain the peak deviator stress also increased with the increase of infill saturation for both peaks.

4 CONCLUSIONS

This paper has discussed the influence if the initial degree of saturation of the infill and the ratio of infill thickness to asperity height (*t/a*) on the shear behavior of idealized saw tooth clay infilled joints. From the experimental results it is clearly shown that the peak shear strength of an infilled joint is decreasing with the increase of infill degree of saturation. Therefore the initial degree of saturation can be considered as a significant factor controlling the overall shear behavior of an infilled joint.Tests conducted under different confining pressures such as 300 kPa and 900 kPa also displayed similar trends proving the significance of the initial degree of saturation of infill.

The joints showed two characteristic shear behaviors based on the thickness to asperity height (*t/a*) ratio. Double peak behavior was observed for the thin infilled joints with (*t/a*) ratios varying from 0.5 to 1.0. Infilled joints with (*t/a*) ratios greater than 3.0 showed a single peak demonstrating the shearing through infill alone. The boundary of these two characteristics can be related to the asperity angle of the saw-tooth joint as well as the infill degree of saturation. This has to be verified by conducting further testing on different joint profiles including natural joints under various saturations of infill.

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