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Shear strength of rock joints influenced by compacted infill

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ABSTRACT

Discontinuities such as fault planes, joints and bedding planes in a rock mass may be filled with different types of fine-grained material that are either transported or accumulated as gouge due to weathering or joint shearing. Previous laboratory studies have mainly examined the role of saturated infill that exhibits the minimum shear strength. However, in practice, the infill materials are often partially saturated generating matric suction within the joint that can contribute to increased shear strength. To the authors' knowledge this is the first study to examine the influence of compacted (unsaturated) infill on the joint shear strength. A series of laboratory triaxial tests on idealised model joints and imprinted natural joint profiles was carried out, with constant water contents of the infill being maintained. From the laboratory results, it is observed that the peak shear strength of infilled joints increased with the decrease of degree of saturation from 85% to 35% for both idealised joints and replicated natural joints. Based on the laboratory observations an empirical model for describing the infilled joint shear strength was developed.

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 rock joint from coming into contact during shear.

The degree of saturation of the infill is a governing parameter of the shear strength of a filled joint, and it can vary noticeably, depending on the groundwater and climate patterns. Barton [1] carried out an extensive study of filled discontinuities in rock in which the in-situ water content of the infill was found to be a principal parameter controlling the shear strength of a filled joint. Furthermore, for adverse climatic conditions, i.e. heavy precipitation and long periods of rainfall, Barton [1] has reported that the joints may act as conduits of water, leaving the fine infill material basically in near saturated conditions. Most rock masses contain complex, interconnected networks of joints filled with gouge material and because of their high transmissivity, joints are often conduits for fluid flow [2]. 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, contributing to an increase in the overall shear strength of the jointed rock mass. While studies have been carried out to investigate the behaviour of infilled rock joints [3–9], the majority have considered either a fully saturated infill condition or a specified saturation level.. Recently, Alonso et al. [10], and Zandarin et al. [11] conducted a study on partially saturated bare rock joints, but the role of infill within the joint was not considered. From a practical perspective, most infill materials will likely be compressed over time and remain typically 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, grouting of the joints may be considered as a method to prevent the infill materials from reaching full saturation, thus reducing the probability of catastrophic rock slides occurring.

The shear strength of a filled joint is often assumed to be that of the infill material alone. While this assumption may be acceptable if the infill thickness is higher than a certain critical value, for smaller values of infill thickness in relation to the joint roughness or asperities it neglects the possibility of rock-to-rock contact taking place. In these conditions, the rock-to-rock contact

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influence becomes increasingly prominent. In contrast, the effect of infill saturation can be distinctly observed for a thicker infill where the strength is governed by the infill alone. This effect decreases as the infill becomes thinner, because in such conditions the shear strength of the joint is basically governed by the shear behaviour of the surfaces of the rock.

In this study, a series of constant water content undrained triaxial tests on idealised models of rock joints and replicated natural 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 [12,13], no literature is available on infilled joints tested under unsaturated infill conditions. This study proposes a novel approach for laboratory testing of infilled joints under different initial degree of saturation of compacted infill.

2. Laboratory investigation

2.1. Specimen preparation

Calibration of any shear strength model requires a series of identical joint specimens, and this surely restricts the use of real joint surfaces. Therefore, for reasons of simplicity and reproducibility, idealised model rock joints with regular saw toothed surfaces were cast with a mean dip angle of 60° [8]. The jointed specimens were 54 mm in diameter with an asperity height of 2 mm and an initial asperity angle of 18°. Fig. 1 shows the mould used to prepare the specimens and a specimen obtained after casting. Indraratna [14] proposed the use of gypsum cement ($CaSO_4 \cdot H_2O$ hemihydrates, 98%) to model soft sedimentary rocks and to prepare idealised joints. This material is readily available and relatively inexpensive and can be moulded into any shape when mixed with water. The unconfined compressive strength is independent of time once the chemical hydration is complete. The properties of the material depend on the gypsum cement to water ratio used to mix it. A consistent unconfined compressive strength (σ_c) of 65–70 MPa was obtained for a plaster to water ratio of 7:2 by weight after two weeks of curing. After being removed from the mould, the plaster specimens were cured for two weeks in an oven at a controlled temperature of 40–45 °C. The plaster specimens were immersed in water for at least 72 h, and subsequently an organic waterproof sealant was applied over the surfaces of the joints to ensure that the infill water content remained constant throughout shearing. Indraratna et al. [8] has shown that this thin layer of waterproofing sealant has negligible effect on the shearing resistance of the joint surface. Additional specimens replicating the roughness profiles of natural joints were also prepared. The details of the preparation method are given in the subsequent sections.

A silty clay (25% fine sand and 75% kaolinite) with a liquid limit of 39 and a plastic limit of 20 was used as the infill material. The shear strength behaviour of the infill material under saturated conditions was studied using a direct shear box apparatus (AS 1289.6.2.2 [15]), and a friction angle of $\phi' = 21°$ and a cohesion intercept (c') of 13.4 kPa were obtained. The infill material was mixed in the laboratory to known moisture contents and then spread over the surfaces of the joints with a spatula. The joints were then statically compacted to a given infill thickness to asperity height (t/a) ratio with an infill dry density of 1250 kg/m^3. Note that despite having infill specimens prepared with varying (t/a) ratios, the initial dry unit weight remained the same, and thus different water content resulted in initial degree of saturations varying from 35% to 85%, corresponding to a suction varying from 860 kPa to 165 kPa (see soil water characteristic curve later). An example of the final joint profile obtained once the infill was spread to a certain thickness is shown in Fig. 1c. Although the behaviour of the joints with infill is studied for a wide range of the infill initial degree of saturation, fully saturated conditions were not considered. This is owing to the difficulty in preparing viable specimens using this procedure, that is, because the infill became slurry-like when it approached saturation. After assembly the infilled joint specimens were wrapped in a thin neoprene (impervious) membrane. During testing, the sealant applied on the surfaces of the joint and the impervious membrane ensured that the clay infilled joints maintained constant water content conditions. Furthermore, as the permeability of the model rock is much lower than that of the infill ($k_{infill}/k_{rock} > 1000$), it could be assumed that undrained conditions would still prevail.

2.2. Testing procedure

The high-pressure two-phase triaxial apparatus (Fig. 2) developed at the University of Wollongong [16] was customised for this study. The cylindrical chamber can accommodate samples of 54 mm and 60 mm in diameter with a height-to-diameter ratio up to 2.0. Silicon oil was used as the confining fluid as it does not react with the steel cell or with the latex membrane. A variable

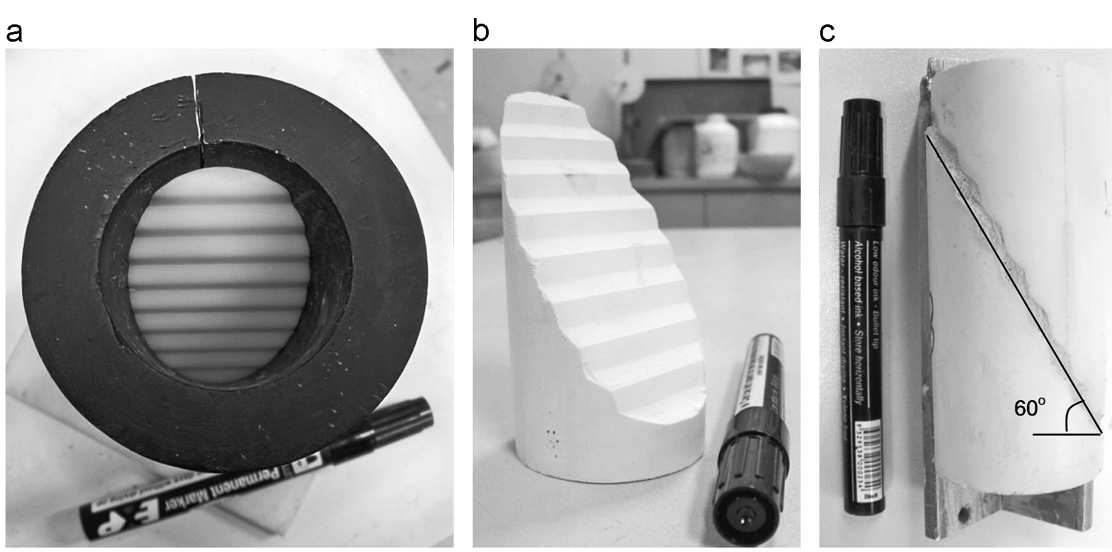

Fig. 1. (a) The mould and (b) simulated joint surface profile of the idealised saw toothed joint (c) with the infill material.