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EXPERIMENTAL AND NUMERICAL MODELLING OF SHEAR BEHAVIOUR OF ROCK JOINTS

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ABSTRACT

The shear behaviour of soft rock joints is investigated in laboratory under both Constant Normal Load (CNL) and Constant Normal Stiffness (CNS) conditions. The laboratory behaviour is modelled numerically using the Universal Distinct Element Code (UDEC). The predicted shear stress, normal stress and dilation behaviour with shear displacements are compared with the laboratory results. It is observed that UDEC can predict the peak shear stress of unfilled joints under CNS, however, it overestimates the joint dilation as well as the normal stress. The maximum peak shear stress in UDEC is attained at a greater shear displacement in contrast to the laboratory observations. The UDEC predictions are generally in good agreement with the laboratory data under CNL condition, where the asperity degradation is found to be less significant.

INTRODUCTION

The correct evaluation of the shear strength of rock joints is imperative in the design of excavations in jointed rocks, and in the stability analysis of jointed/bedded rock slopes. Currently, the shear strength of rock joints is mainly assessed in the laboratory using the conventional direct shear apparatus, where the shear load is varied while keeping the normal load constant (ie. CNL method). However, for non-planar or rough discontinuities, shearing causes dilation of the joints as asperities ride over each other (Ohnishi & Dharmaratne, 1990; Kodikara & Johnston, 1994; Haberfield & Seidel, 1998 and Indraratna et al. 1999). If the surrounding rock mass is unable to deform sufficiently, then an inevitable increase in the normal stress occurs during shearing. The stiffness of the rock normal to the joint, however, can be assumed to be constant (CNS), even though the normal stress changes. Therefore, the CNL condition is often unrealistic in circumstances where the normal stress in the field changes considerably during the shearing process. In view of this, laboratory testing is required to be carried out under changing normal stress condition, thereby making the mode of shearing to occur under constant normal stiffness (CNS).

For the last two decades, researchers have been involved in the modified design of direct shear apparatus for a wide range of applications, where the accuracy of shear strength parameters was considered to be very important [e.g. Skinas et al. 1990; Ohnishi & Dharmaratne, 1990]. In the mid 1980's, Monash University (Melbourne) designed a direct shear apparatus for finding the side shear resistance of rock socketed piles under CNS condition (Johnston et al. 1987). This apparatus could also be used for conventional shear testing of joints, ie. CNL condition. In the past, shear behaviour of hard concrete and cement mortar joints as well as natural hard rock joints have been investigated using the CNS technique. However, the shear behaviour of soft rock joints under CNS conditions is not yet well understood. This study is an attempt to model and investigate the shear behaviour of soft joints under CNS conditions, using a specially designed CNS shear equipment designed by the authors (Figure 1).

The shear behaviour under both CNL and CNS is modelled using Universal Distinct Element Code (UDEC). The material properties and the normal stiffness are assigned in the model to closely simulate the laboratory shear conditions. The behaviour of selected saw-tooth joints (gypsum plaster) having an inclination of 9.5^{o} has been modelled. The predicted behaviour is compared with that of the laboratory data, and it is observed that the predicted peak shear stress based on UDEC is in acceptable agreement with the laboratory data, if the asperity degradation during shearing is insignificant.

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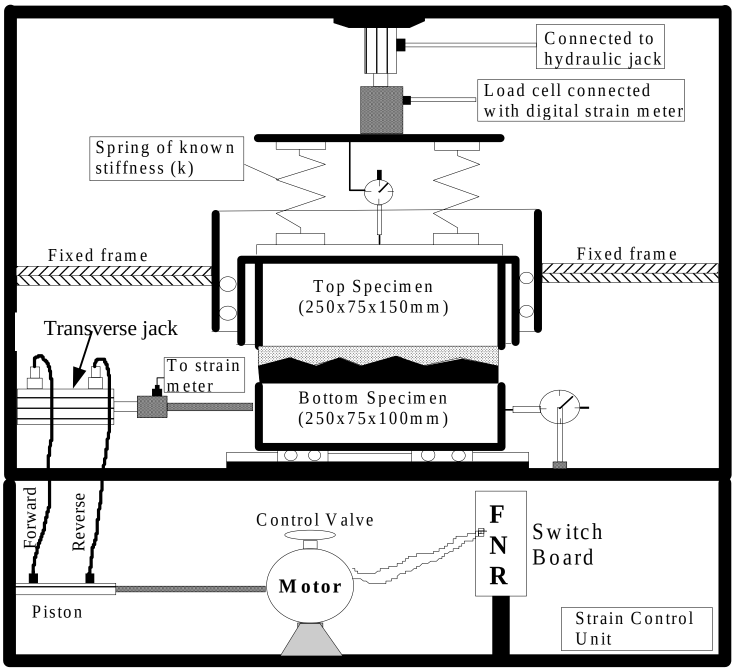

Figure 1. Schematic diagram of the CNS shear apparatus (Indraratna et al. 1998).

UDEC ANALYSIS OF SHEAR BEHAVIOUR OF JOINTS

Choice of Joint Models

UDEC (Universal Distinct Element Code) has been used successfully to model the shear behaviour of jointed rocks, flow through discontinuities and slope stability problems. The different joint models that can be used in the UDEC program are outlined below.

The simplest model for simulating discontinuity strength is the linear Mohr-Coulomb friction model. This model is sufficient for smooth discontinuities such as faults at residual strength, which are non-dilatant. The other models such as the Barton-Bandis model and continuously yielding model may be more appropriate to explain the non-linear behaviour often encountered in rough rock joints. The Barton-Bandis model takes into account more features of discontinuity strength and deformation behaviour than the Coulomb model.

The continuously yielding model (Cundall & Hart, 1984) is designed to provide a coherent and unified discontinuity deformation and strength model for joints undergoing both elastic and plastic deformations. In this numerical study, the continuously yielding joint (CYJ) model is employed. Further details of CYJ model and its use in jointed rock is described in the UDEC manual.

UDEC shear modelling and simplifications

The CNS direct shear boundary conditions used in UDEC are shown in Figure 2(a), which simulate the laboratory conditions as accurately as possible. The material properties of the top block (A) are prescribed (shear modulus=35 MPa; bulk modulus=23 MPa) in such a way that the external stiffness (8.5 kN/mm) applied by the spring system is modelled explicitly. The blocks B and C are discretised according to the laboratory specimen size (Figure 2b), and are assigned the material properties of the model joint tested in this study (shear modulus=792 MPa; bulk modulus=1400 MPa). Once the blocks are formed and their representative material properties are assigned, they are discretised by a triangular mesh. A low density mesh is used for block A, whereas a fine mesh is prescribed for blocks B and C (Figure 2b).

At first, the initial normal stress (σ_{no}) is applied to the joint and the model is allowed to reach equilibrium. A horizontal velocity is applied to the bottom block (C) to produce the required shear displacement compatible with laboratory shear rate. The average normal and shear stresses along the joint are applied using a FISH function. The associated dilation and shear displacements are also calculated via FISH functions. From the shear stress vs displacement plot, the peak shear stress for the applied normal stress can be determined. The interface asperity shape (triangular) is input via ‘crack commands’ and subsequently, the joint material properties are assigned through FISH functions.

The conventional direct shear test (CNL) is modelled in UDEC in a similar way as in CNS, the only exception being that the top block A (Figure 2) is deleted, and the top specimen boundary along the y-direction is made free. This enables dilation to take place under k_n=0 condition.

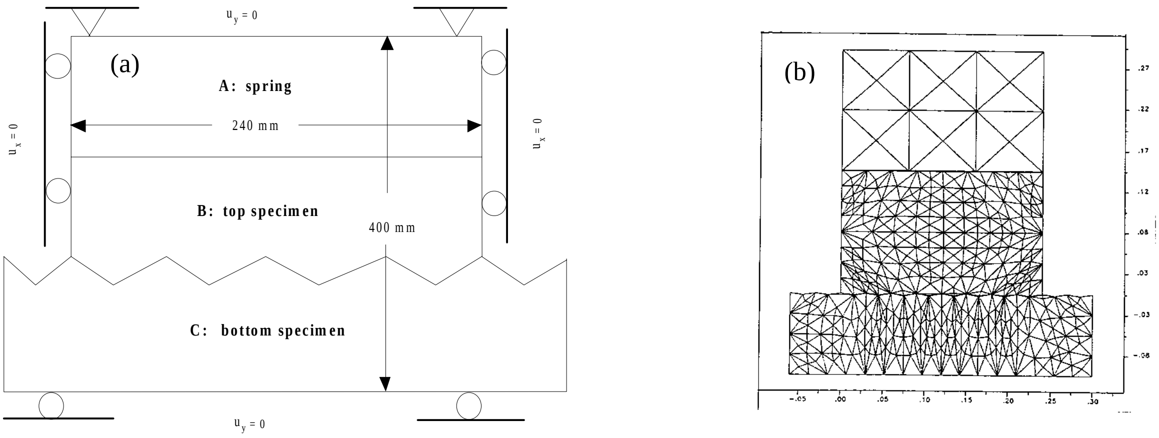

Figure 2. (a) Conceptual model for laboratory CNS shear behaviour and (b) discretisation of blocks

EXPERIMENTAL STUDY

In order to investigate the shear behaviour of soft rock/rock interface and infilled joints, a large scale shear apparatus was designed by Indraratna et al. (1998), which could also be used to test specimens under both CNL and CNS conditions (Figure 1). The direct shear apparatus designed for this study consists of a pair of large shear boxes, the shear and normal loading devices, and displacement monitoring transducers. All the tests were carried out at a shear displacement rate of 0.50 mm/min.

The shear behaviour of soft rock joints was studied by conducting a comprehensive testing program on a series of modelled saw-tooth joints under both CNS and CNL conditions. At first, tests were conducted under CNS on a series of unfilled/clean saw-tooth joints having an asperity angle, i=9.5^o for varying initial normal stress (σ_{no}). In order to compare the shear behaviour of joints under CNS with CNL, additional tests consisting of saw-tooth joints of inclination 9.5^o were conducted under CNL condition. Tests were conducted under four different σ_{no} values of 0.56, 1.10, 1.63 and 2.43 MPa.

Preparation of joint specimens

Gypsum plaster ($CaSO_4.H_2O$ hemihydrate, 98%) was used to make idealised soft rock joints, mainly because this material is universally available and is inexpensive. The cured plaster showed a consistent uniaxial compressive strength (σ_c) in the range of 11 to 13 MPa and a Young's modulus (E) of 1.9 to 2.3 GPa. It is found to be suitable for simulating the behaviour of a number of jointed soft rocks such as coal, friable limestone, clay shale and mudstone (Indraratna, 1990).

The top and bottom moulds needed to be detached from the shear apparatus before casting the upper and lower portions of the specimen inside them. In this study, plaster was initially mixed with water in the ratio of 5:3 by weight. Subsequently, the bottom mould together with the adjustable collar was filled with the mixture, and left for at least an hour to ensure adequate hardening before casting the upper specimen. Naturally, the collar was shaped according to the desired surface profile. In this study, triangular asperities with angles of inclination of 9.5^o (Type I) were used. After one joint profile was cast, the top mould was then placed over the bottom mould and filled with the plaster mixture. A thin polythene sheet was inserted between the two moulds separating the two fully mated joint surfaces, and the whole assembly was subsequently cured for another hour at room temperature to complete initial setting. During specimen preparation, mild vibration was applied to the moulds externally to eliminate any entrapped air. After initial hardening, the moulds were stripped and the specimens were cured at 50^o C inside an oven for two weeks. Before testing, the specimens were allowed to reach the room temperature.

RESULTS AND DISCUSSION

Tests were conducted on many specimens of identical regular saw-tooth profiles in the large shear apparatus under Constant Normal Stiffness (k=8.5 kN/mm), as well as under constant normal load (CNL) conditions. The same initial normal stresses (σ_{no}= 0.56, 1.10, 1.63 and 2.43 MPa) were used in all tests. The variation in shear stress with horizontal displacement was recorded at every 0.5mm interval via a load cell, which was connected to a digital strainmeter. The shear stress response for the Type I saw-tooth joints under various σ_{no} is shown in Figure 3. It is observed that as σ_{no} is increased, the peak shear stress is generally increased, as expected (note that the vertical axis of the four plots in Figure 3 are not the same scale).

The variation of normal stresses was recorded through a digital strainmeter as shearing was progressed. For various initial normal stresses (σ_{no}), tests were conducted to derive the relationships between the average normal stress, dilation and shear stress as a function of the horizontal displacement. The normal stress is expected to increase when the asperities on the top half of the joint override those on the bottom half, until the 'peak to peak' contact is made to give the maximum dilation. The subsequent downward movement or reduced dilation (ie. mating of non-degraded joints) should indicate a gradually decreasing normal stress (see Figures 4 and 5 and the corresponding discussion later). However, at considerably high normal stress levels (say σ_{no} greater than 2 MPa), this trend may not be expected because of the degradation of asperities.

The average shear stress vs horizontal displacement along the joint under CNS is plotted in Figure 3 together with the experimental data for selected tests. It is observed that the predicted peak shear stress based on UDEC is in acceptable agreement with the laboratory data, although the pre-peak shear stress response is somewhat underestimated. The predicted shear stress increases with the horizontal displacement and shows a maximum value approaching the peak-to-peak contact of the asperities. In contrast, the laboratory peak shear stress is observed to occur at a smaller horizontal displacement, in comparison with UDEC analysis. At increased levels of initial normal stress (σ_{no}), the asperity crushing is significant as reflected by much smaller dilation than that shown by UDEC data (Figure 4), and in this particular case, UDEC prediction of shear stress is considerably smaller than the observed data (Figure 3). Asperity degradation cannot be modelled using UDEC, which tends to under-predict the shear stress values. This is reflected from Figure 4, where enhanced dilation is predicted by UDEC analysis. It is not surprising to note that the UDEC predicted dilation vs shear displacement curves in Figure 4 follow the shape of triangular asperities, in the absence of simulating asperity breakage.

The average normal stress variation under CNS along the joints for various σ_{no} values is plotted in Figure 5. Under CNS, the normal stress increases during asperity overriding (Figure 5), and if the localised stress concentrations exceed the compressive strength of material, asperity degradation occurs. The maximum possible normal stress should occur if the peak to peak contact of asperities would take place, as predicted by UDEC. However, if the initial normal stress, σ_{no} is high, degradation occurs even before the peak to peak contact of asperities is reached, as indicated by the test results in Figure 5. As the dilation of the joint is overestimated by UDEC, the corresponding normal stress is also overpredicted. The peak shear stress occurs at a greater shear displacement for UDEC in comparison with the laboratory results. After attaining the peak, the shear stress continues to decrease with the shear displacement of the joint. The predicted shear stress vs horizontal displacement plot under CNL is shown in Figure 6 for comparison.

Under conventional CNL, the laboratory observations verified that the asperity degradation is less prominent at the same initial normal stress and at similar shear displacements. It is observed that under CNL, the peak shear stress is attained at a smaller horizontal displacement in comparison with Figure 3 for CNS testing. In conventional CNL testing at low normal stresses, UDEC predictions are closer to the observed laboratory data, as the asperity crushing is less significant. This leads to the conclusion that UDEC is more appropriate in modelling CNL behaviour at insignificant asperity degradation. It is beyond the scope of this study to attempt to modify UDEC capabilities to accommodate realistic asperity crushing, and thereby accurately model shearing under the CNS condition.

Test results of this investigation verify that the shear behaviour of soft joints under constant normal stiffness (CNS) is different to the conventional shear response observed under constant normal load (CNL) conditions. In CNS testing, the extent of dilation becomes pronounced with shearing and the apparent normal stress varies accordingly. It has been observed that the CNL condition always overestimates the dilation of joints, thereby underestimating the actual peak shear stress corresponding to the field conditions (Indraratna et al. 1998). It is observed that at elevated σ_{no} values, the measured dilation becomes smaller.

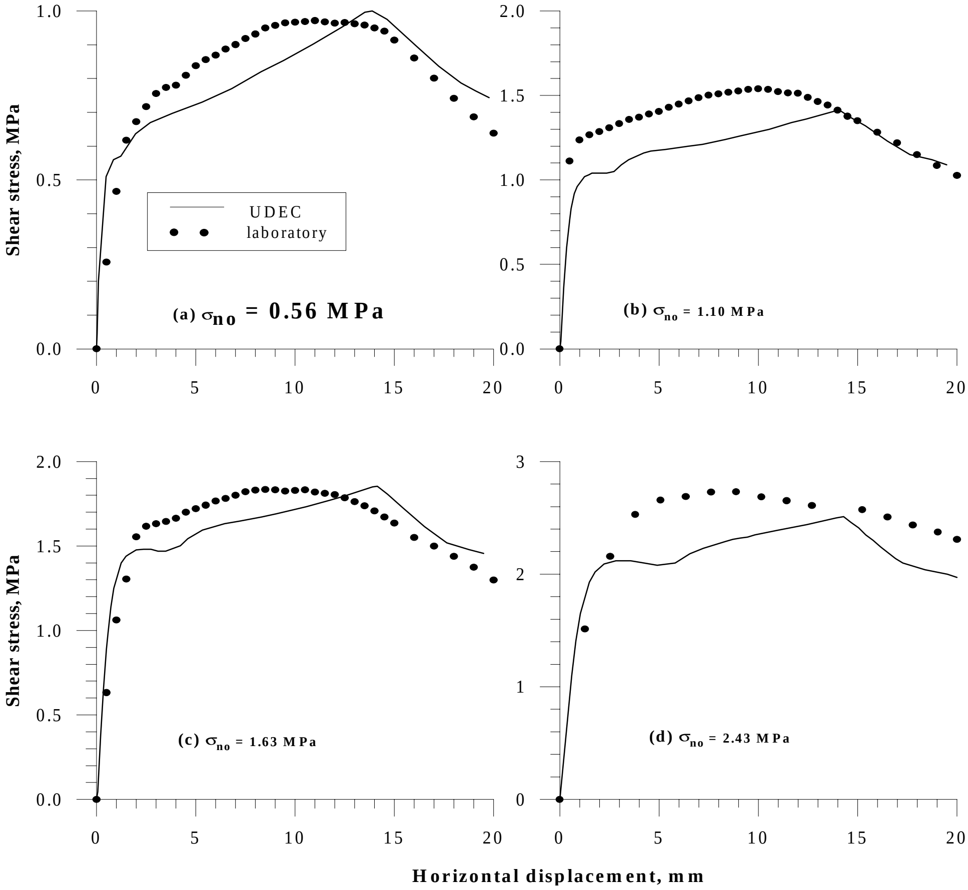

Figure 3. UDEC prediction and observed shear stress responses for Type I joints under CNS.

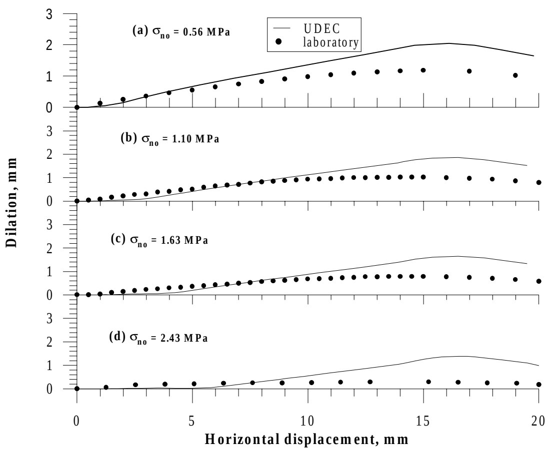

Figure 4. UDEC prediction and observed dilation behaviour of Type I joint under CNS.

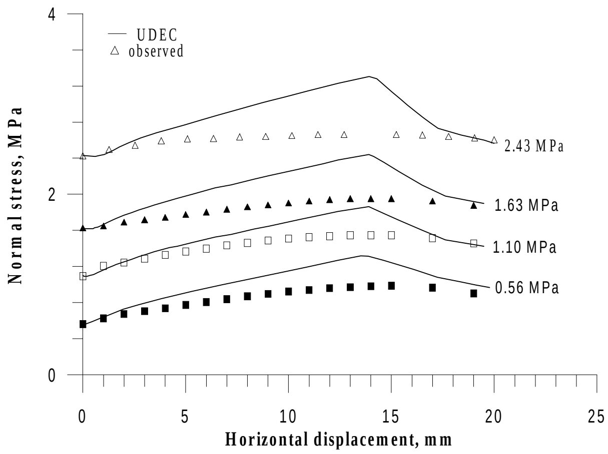

Figure 5. UDEC prediction and observed normal stress responses for Type I joint under CNS.

CONCLUSIONS

The shear behaviour of simulated joints was analysed using the Universal Distinct Element Code (UDEC) in a simplified manner. For a given set of initial normal stresses, the variations of the average normal stress, shear stress and dilation with the horizontal displacement were studied. The UDEC predictions were compared with the laboratory results observed for these plaster cast, saw-tooth joints.

The results indicate that If UDEC is employed to analyse the peak shear stress of unfilled joints under CNS, the predictions overestimate the joint dilation and the corresponding normal stress. The maximum peak shear stress in UDEC is attained at a greater shear displacement in contrast to the laboratory data.

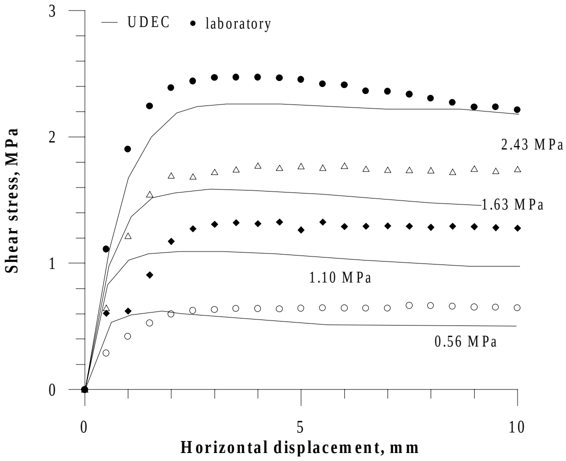

Figure 6. UDEC prediction and laboratory shear behaviour of Type I joint under CNL.

Nevertheless, the UDEC predictions are generally in good agreement with the laboratory data observed for the conventional CNL testing, where the asperity degradation is found to be less significant. Naturally, this also implies that for planar joints, the difference in shear behaviour between CNS and CNL is insignificant.

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