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Discrete element method simulations of analogue reservoir sandstones

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ABSTRACT

The Discrete Element Method was used to model the behaviour of two natural sandstones that are commonly used as analogues for oil reservoir sandstones. With a relatively large number of parameters needed to define the model and few micro-scale data on which to base them, a parametric study was first carried out to identify how each parameter affects the overall macroscopic behaviour. This study highlighted the importance of the load share between the particle contacts and the bonds. The model for the more strongly cemented sandstone was calibrated against the response observed at a single stress level and predictions at other stress levels were then found to be good. A second, more weakly cemented, sandstone was also modelled. It was found that while this sandstone had a very much lower cement content by weight, only minor modifications were needed to the bond strengths and the proportion of bonded contacts compared to the more strongly bonded material. This may be because of the failure to model the natural fabric of the sandstones. In general the post-peak regime was not modelled well, nor was the volumetric response, the latter as a result of the failure to achieve the in-situ porosities in the model.

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1. Introduction

The potential of the Discrete Element Method (DEM) to simulate rock behaviour, especially phenomena at a particle scale, is well established, but a key difficulty is the selection of appropriate parameters both for the elements and the bonds connecting them. Potyondy and Cundall [1] used a particle bonded model to capture the behaviour of Lac du Bonnet granite and in comparisons between the macroscopic parameters generated by the DEM and measurements, they found that while Young's modulus (E), Poison's ratio (ν) and unconfined compressive strength were well modelled, the angle of shearing resistance (ϕ) and the Brazilian tensile strength were not. This, they concluded, was the result of the circular/spherical particle geometry and unbreakable nature of the grains. Cho et al. [2] found that better matching could be achieved modelling more complex particle shapes with clumped particles consisting of a number of elements held together with unbreakable bonds and Yoon et al. [3] drew similar conclusions.

Fakhimi and Villegas [4] developed a dimensional analysis technique for choosing DEM parameters, producing charts relating the parameters to macroscopic properties. Their work was, however, in 2D, and most examples of parameter selection in 3D have remained by trial and error. The present paper describes a systematic investigation of effects of micro-parameters in the modelling of macro-behaviour for sandstones. Capturing the rock behaviour in single element tests on the sandstones was seen as necessary first step in an investigation of sand production in oil wells in which thick walled cylinder tests were modelled. It might be expected that DEM would be capable of modelling even better the micro-mechanics of sandstones than the behaviour of crystalline rocks, because their porosities are higher and they have discrete particles bonded by cement at the contacts, in a similar manner to the DEM model. The potential of DEM to investigate sand production under fluid flow into an oil well has been recognised by a number of researchers [5–8].

The rocks modelled here were the Castlegate and Saltwash sandstones, which outcrop in Utah, USA, and are used by the oil industry as analogue materials. They were tested in the laboratory by Alvarado et al. [8,9], among others, and it is their high pressure triaxial tests, as well as others reported by Coop and Willson [11] that were modelled. The void ratios of the Castlegate and Saltwash sands are 0.33 and 0.42 respectively (porosities 0.25 and 0.30) and they have mean particle diameters of 0.11 and 0.18 mm. The Castlegate sandstone is more heavily cemented with 6.4% cement content by weight compared to 1.8% for the Saltwash. Drained triaxial tests were carried out over a range of effective cell pressures with very accurate measurement of the local axial strain by means of an LVDT system [12]. Extensive databases for high

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quality triaxial testing of sandstones at high pressures are quite rare in the literature, and with the possibility of comparing a weakly and a more strongly cemented sandstone with similar mineralogies and geological histories, this database is particularly suitable for evaluating and calibrating the DEM models.

2. Modelling approach

The analyses were carried out in PFC3D and in common with the previous research by [1,4] a parallel bond model was adopted. This is similar to that developed by Jiang et al. [13], the advantage being that in contrast with a simple contact bond, the parallel bond can transmit moment as well as compressive and tensile load. It is therefore believed to replicate better the effects of natural cement, especially in a model where the DEM elements are simple spheres which would otherwise have no rolling resistance arising from their shape.

A schematic diagram of a parallel bond is given in Fig. 1. The parallel bond has a finite width that must be less than the diameter of the smaller of the contacting particles and is defined by α_{bond}. The bond acts in combination with the normal contact spring for the two elements. Here, for simplicity, a linear contact model has been used for both normal and tangential loading. Even if we conceptually think of a cylindrical bond as in the figure, the parallel bond does not model the actual cement, as was done for example by Wang and Leung [14] who used multiple small DEM elements to represent the volume of cement. Although it does not capture the geometry of the cement the parallel bond is numerically more efficient and so allows a much greater number of particles to be modelled. However, the list of parameters that needs to be chosen is quite long because there are input parameters both for the contact and the bond and the load share between them will depend on the properties of each. In addition to the normal and shear stiffnesses for the contact, K^N and K^S (units kN/m) there are the stiffnesses of the parallel bond for normal and shear loading, K^N_{pb} and K^S_{pb} (units kPa/m). The strengths of the bond in tension and shearing are S^N_{pb} and S^S_{pb} (units kPa). The size of the bond is given by $R_{bond}=\alpha_{bond}\ \min(R_a,R_b)$, where R_{bond} is the bond radius, R_a and R_b are the radii of the two contacting particles, and α_{bond} is a dimensionless parameter specified by the user. Finally a coefficient of inter-particle friction, μ, is required for the frictional resistance to sliding at the contact. The use of two contact models in parallel leads to a relatively large number of parameters and great flexibility in modelling, even if the behaviour of real cemented contacts is unlikely to be so simple. Unfortunately, few of the parameters can be related to any real test data at the particulate level and so the degree of freedom in choosing the parameters is daunting. For convenience in comparing the effects of the contact and parallel bond stiffnesses, which have different units, the parallel bond stiffnesses K_{pb} will by multiplied by the contact area to give equivalent parallel bond stiffnesses $K_{eq,pb}$ with the same units as the contact stiffnesses, K_c.

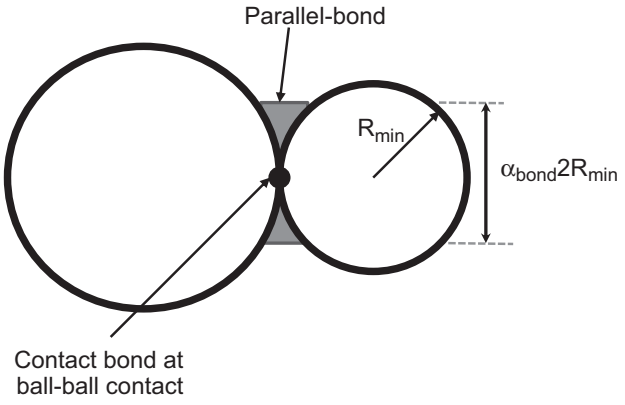

Fig. 1. Schematic illustration of parallel a bond model.

Fig. 2 shows the results of a simple two particle test that gives insight into parallel bond performance. The values of the contact and equivalent parallel bond stiffnesses, K_c and $K_{eq,pb}$, were the same and so, in compression, when the normal force is greater than 0, the load is shared equally between the contact and the bond as the particles are moved closer together and then further apart. In tension (normal force <0) the contact takes no load and so the overall load–deflection curve changes gradient which governs by $K_{eq,pb}$. The bond fails at a load defined by the strength and area, after which the interface reverts to the simple contact model and the bond disappears. The gradient of

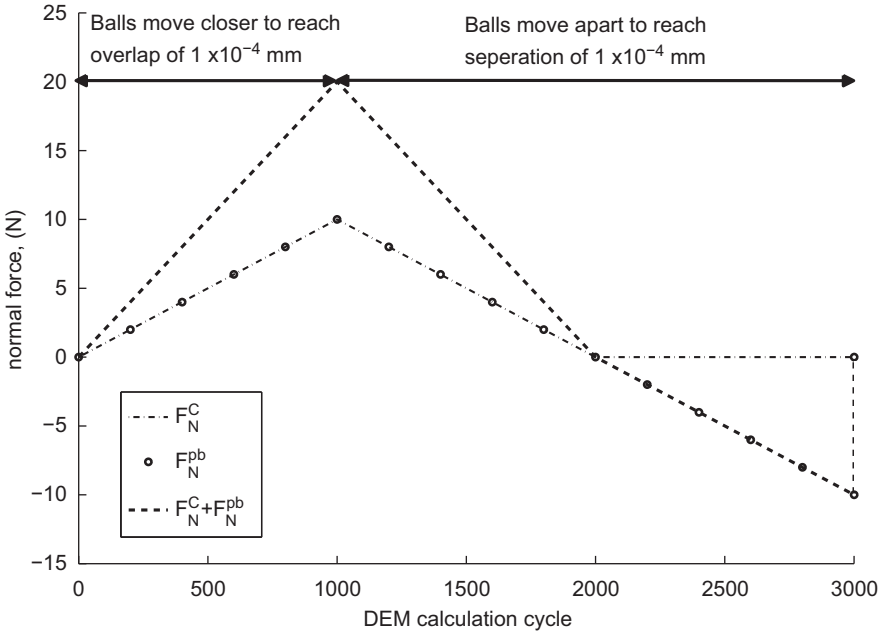

Fig. 2. Behaviour of contact bond under compression and tension.

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