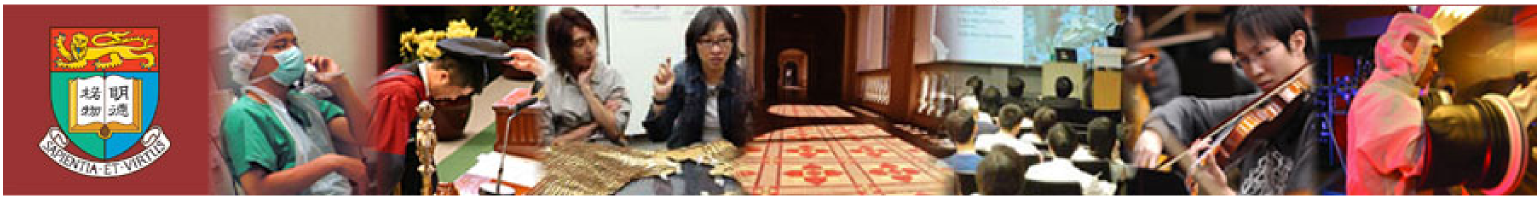

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DISCUSSION / DISCUSSION

Discussion of “Forms and sand transport in shallow hydraulic fractures in residual soil”[1]

S.K. Alfred Au and Albert T. Yeung

The authors should be commended for their long-term extensive research effort in hydraulic fracturing (Murdoch 1993*a*, 1993*b*, 1993*c*). In the investigation under discussion, four sand-filled hydraulic fracture tests were carried out to better understand the forms of hydraulic fractures created in shallow saprolite and to compare them with those in other geologic materials under similar conditions. It was observed by the authors in their field experiments that the fractures were shaped like slightly asymmetric saucers that were roughly flat-lying in their centers and slightly curve upwards. In fact, similar fracture pattern was observed in laboratory experiments on hydraulic fracturing conducted by injecting cement bentonite and epoxy into clay specimens with overconsolidation ratio of 5 under similar free surface boundary condition (Chin 1996; Au 2001; Au et al. 2003, 2005; Soga et al. 2003). It has also been demonstrated experimentally in the laboratory that hydraulic fracture may be initiated by injecting a small volume of fluid into highly overconsolidated clay. The fracturing fluid then propagates along the initiated cracks, perpendicular to the direction of major principal stress, and develops them into large fractures afterwards.

A theoretical model of hydraulic fracture propagation has been developed by the authors by adapting the software Fran2d under the framework of linear elastic fracture mechanics to explain the observed fracture forms. The discussers agree with the authors wholeheartedly that understanding of the controls on fracture form has useful applications. However, there are some points presented in the paper that are worth discussing and clarifying.

It is unclear to the discussers why the hydraulic fractures were created in the B horizon above the saprolite while “the primary objective of the investigation is to describe the forms of hydraulic fractures in saprolite and compare them with the forms created in other geologic materials.” It is evident from the authors’ description that the material properties of B horizon are quite different from those of saprolite.

As the degree of saturation of the specimens is well below unity, the accuracy of the results of unconsolidated–undrained (UU) triaxial tests in describing the stress–strain characteristics and quantifying the shear strength parameters is doubtful. Increase in effective stress within the specimens can still occur with the increase in confining stress even in the UU test. The argument is substantiated by the fact that the friction angle of the soil measured by the authors decreases when the confining stress increases.

The modulus of elasticity of soil, determined by the UU test, may not be appropriate for the numerical simulation of the tensile failure fracture. The modulus of elasticity of soil is very dependent on its strain. It is well known that the modulus of elasticity of soil determined by the triaxial test is considerably lower than its actual value in the field, as the strain is considerably higher.

The K_o value determined by Malin (2005) in his hydraulic fracture experiment is quite different from that obtained by the authors using flat-blade dilatometer measurements in the same project. The authors may have to elaborate on their choice of the K_o value used in their numerical simulations.

The fracture toughness (K_{IC}) was introduced as a parameter used to estimate the fracturing pressure by Murdoch (1993*b*). The measured fracturing pressure of approximately 300 kPa is approximately 9 times the undrained shear strength, i.e., 34 kPa. The result is consistent with the theoretical ultimate cavity expansion pressure in soil (Au et al. 2006). However, the magnitude of fracturing pressure is dependent on injection rate and overconsolidation ratio of the soil (Mori and Tamura 1987; Au 2001; Soga et al. 2003), as shown in Fig. D1, where P_f is the fracturing pressure and σ'_v is the effective overburden pressure. However, both the injection rate for the experiments and the overconsolidation ratio of the soil were not given in the paper.

On the basis of the given K_o value, the discussers envisage that the soil is highly overconsolidated. As a result, the soil may behave elastically. Therefore, the use of linear elastic fracture mechanics to simulate the fracture propagation process may be appropriate. Otherwise, the applicability of elastic analysis in hydraulic fracturing should be carefully considered. However, the adjusted intrinsic soil parameters obtained by the authors assuming the validity of the approach is worth discussing. It was concluded by Murdoch (1993*b*) that “When soil is completely saturated, K_{IC} is essentially zero. Nevertheless, well-developed hydraulic fractures were created in soil of negligible toughness.” The ex-

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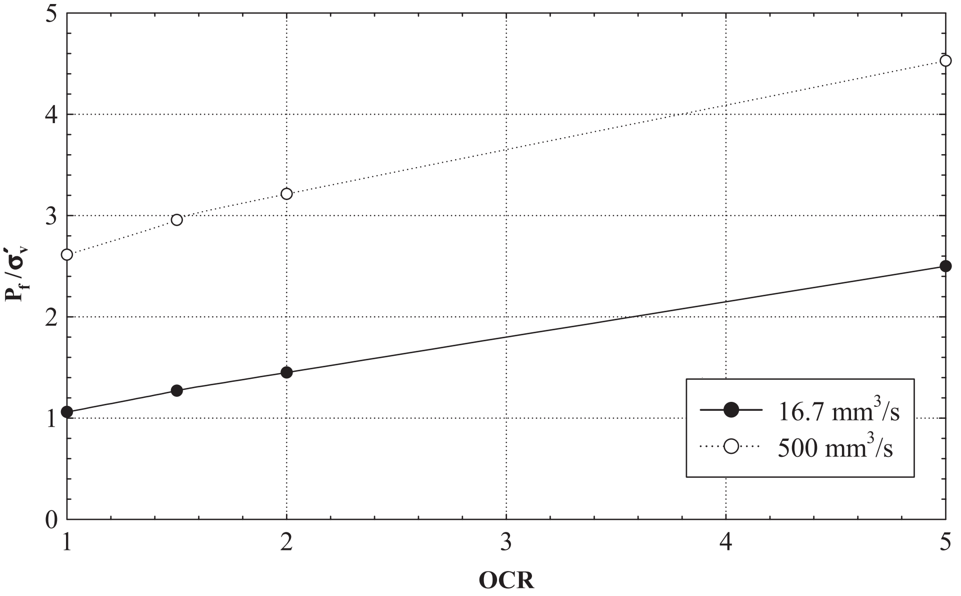
Fig. D1. Normalized fracturing pressure versus OCR at different rates of injection (after Au 2001).



perimental data presented by Murdoch (1993*a*, 1993*b*) also indicate that the value of K_{IC} is very small as long as the soil is practically fully saturated, regardless the soil is compacted or consolidated. The degree of saturation of the soil at 1.5 m below ground surface in this investigation is 0.99. However, the adjusted value of fracture toughness K_{IC} is determined to be approximately 300 kPa·m$^{0.5}$ by numerical simulations. The authors may have to explain the significant difference in the values of K_{IC} in these two investigations, as both soils are almost fully saturated.

The discussers consider the results of the authors' in situ hydraulic fracture experiments provide useful information to improve our understanding of the fundamental mechanisms of hydraulic fracturing. However, further investigation is still required to develop a thorough understanding of these complex mechanisms.

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