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Numerical and experimental investigation of hydraulic fracturing in Kaolin clay

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ABSTRACT

A coupled model for heterogeneous geomaterials taking into account the fluid flow, element damage evolution and their cross-coupling was used to investigate the hydraulic fracturing behavior of Kaolin clay. The agreements between numerical results and analytical solutions suggest that the coupled model is an appropriate for the study of flow-related problems such as hydraulic fracturing. Using the coupled model, a series of numerical tests on hydraulic fracturing was carried out to study the fracture pattern of hydraulic fracturing under various radial boundary and fluid injection rates. In addition, laboratory tests were also conducted under various radial boundary conditions and fluid injection rates for normally or lightly consolidated and heavily over-consolidated clay. The numerical simulations and experimental results show that the fracture patterns of hydraulic fracturing in clay greatly depends on the size of radial boundary and fluid injection rate, and the fracturing orientation induced by hydraulic fracturing can be controlled by changing the size of radial boundary and fluid injection rate.

1. Introduction

Hydraulic fracturing is the formation of cracks in geomaterials due to excessive fluid pressures induced by liquids being pumped into the formation at high pressure and high rate of flow. Hydraulic fractures are created in the vicinity of a borehole when fluid is injected at a pressure that exceeds some critical value. The technique of hydraulic fracturing has been widely used in petroleum engineering, mining, grouting processes and embankment dams for many years, but its importance in geotechnical engineering has not been considered until recently. In the last decade, much attention has been paid to the application of hydraulic fracturing in clay, and the effect and mechanism of hydraulic fracturing in clay has also been gradually recognized in connection with pressure grouting (Andersen et al., 1994; Au, 2001; Jaworski et al., 1981; Mori and Tamura, 1987). Many investigators have carried out some preliminary and valuable work in this regard. For example, Bjerrum and Anderson (1972) investigated the in-situ measurement of lateral pressure in clay and demonstrated that if the coefficient of earth pressure at rest, K_0, is less than one, a vertical crack will form. Bjerrum et al. (1972) performed in-situ outflow permeability tests to evaluate the effect of hydraulic fracturing in soils. Massarsch (1978) used, C_r, a critical ratio of effective stress change in the plastic zone around expansion cavities, to determine the orientation of fractures in clays based on the theory of cylindrical cavity expansion. He concluded that vertical fractures would form when C_r is larger than unity and horizontal fractures would be generated when it is less than unity. Moreover, he indicated that cracks would be likely to occur along vertical planes during hydraulic fracturing tests in clay, independently of the coefficient of lateral earth pressure, K_0. Hassani et al. (1983) observed the vertical patterns of cracks for all the specimens tested during hydraulic fracturing around a borehole, but the coefficient of lateral pressure K_0 or other related parameters of the specimens in his tests was not specified. Lefebvre et al. (1991) pointed out the fracture pattern was dependent on the length of piezometer tips, the fissures around standard or long piezometer tips being radial and vertical, but the fractures around very short piezometer tips being a combination of horizontal, vertical and inclined fissures. In addition, the coefficients of lateral pressure K_0 at which the in-situ tests were conducted in field sites were all believed to be above unity. Reed and Dusseault (1997) investigated the variations of hydraulic fractures orientation in non-cohesive soil using laboratory experiments and field tests and observed that only vertical fractures occurred in some tests and

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Nomenclature

C'	effective stress cohesion intercept, kPa
C_r'	residual cohesion intercept, kPa
D	damage variable, D=0–1
E	Young's modulus for element, MPa
E_0	average Young's modulus for the elements, MPa
K_0	coefficient of lateral pressure at rest
$K_{0,nc}$	coefficient of lateral pressure for the over-consolidated soil
OCR	over-consolidated ratio
ϕ'	effective stress angle of friction, deg
ϕ_r'	residual effective stress angle of friction, deg
m	homogeneity index
n	a constant
ε_{ij}	strain tensor
ε_v	volumetric strain
u_i	displacement tensor
α	coefficient of pore-fluid pressure
β	coupling parameter
ξ	damage factor of permeability
η	residual coefficient ranging from 0 to 1
k	coefficient of permeability
k_0	coefficient of permeability at stress-free
δ_{ij}	Kronecher delta
σ_{ij}	total stress tensor, kPa
σ'_{ij}	effective stress tensor, kPa
σ_t'	tensile strength, kPa
σ_{tr}'	residual tensile strength, kPa
ε_{t0}	tensile strain at elastic limit
ε_{tu}	ultimate tensile strain
τ	shear strength for the elements, kPa
τ_0	average shear strength for the elements, kPa
H	the constitutive constant characterizing the coupling between the solid and fluid stress
P	fluid injection pressure, kPa
λ	lame constant
G	modulus of shear deformation
Q	specific storage coefficient at constant strain

vertical fractures as well as horizontal fractures in other tests. Au (2001) carried out an experimental study of compensation grouting in clay. All these contradictory opinions and conclusions about pattern of hydraulic fracture indicate that the hydraulic fracturing in clay is not yet fully understood and more detailed numerical and experimental investigations are needed to have clear insight into the mechanism of hydraulic fracturing in clay.

On the basis of needs of geotechnical engineering in fields, the study described in this paper aims to understand the mechanisms of hydraulic fracturing in clay, to investigate the factors influencing the orientation of hydraulic fractures in the cores of embankment dams and soil foundations based on numerical and experimental modeling, and to understand how to practically control the hydraulic fracturing orientation by changing the main influencing factors of hydraulic fracturing.

2. Numerical model

2.1. Brief description of the model

Numerical simulation is currently one of the most popular and effective methods used for investigating and modeling the deformation and failure behavior of geomaterials. For example, statistical modeling has been used for analysis in soil (Ghanem and El-Mestkawy, 1996). A finite element method coupled with a finite difference time stepping scheme has been applied in the simulation of an unsaturated clay soil (Thomas and Rees, 1993) and a finite element based procedure is suggested for the modeling of the hydraulic fracturing of heterogeneous rocks on a macroscopic scale (Wangen, 2011). Some discrete element codes, including Hydrofrac (Thallak, 1992), Ellipse2 (Ng, 1994), have been developed and used to study the mechanical behaviors of granular soil. Even though process has been made in the numerical simulation of deformation and failure occurring in geomaterials, there is a lack of satisfactory models which can simulate the progressive failure process in a more visual way, including the simulation of the failure process, and the stress and flow pressure redistribution induced by failure, etc. The demand for new tools, which may contribute to a better understanding of the failure mechanisms of geomaterials, initiated the development and improvement of flow-coupled rock-like materials failure process analysis code, abbreviated as F-RFPA^{2D} (Tang et al., 2002; Yang et al., 2011, 2004). In F-RFPA^{2D}, we rely on the finite element method to perform stress analysis of the model which is the main part of RFPA^{2D}. Since the details of main code RFPA^{2D} have been described elsewhere (Tang, 1997; Tang et al., 2000, 1998), only the main features and the principle of coupling between flow, damage and stress are described here.

Similar to RFPA^{2D}, the flow-coupled F-RFPA^{2D} code introduces the heterogeneity or inhomogeneity of soil properties and the reduction of material parameters after element failure into the model. For heterogeneity, the model is discretized into a large number of small elements to take into account the local variations of the material heterogeneity. The material properties parameters (shear failure strength and cohesion, etc.) for elements are randomly distributed throughout the specimen by following a statistical Weibull distribution (Weibull, 1951). The statistical distribution function for shear failure strength is given by

$$f(\tau) = \left(\frac{m}{\tau_0}\right) \cdot \left(\frac{\tau}{\tau_0}\right)^{m-1} \exp\left[-\left(\frac{\tau}{\tau_0}\right)^m\right] \tag{1}$$

where τ is the shear failure strength of the individual element; τ_0 is the scale parameter of the elements for the specimen, which is related to the mean shear failure strength of all the elements; and m is the homogeneity index of soil. The higher the homogeneity index value of m is, the more homogeneous the shear failure strength of the elements in the soil is, and vice versa. Fig. 1 shows the statistical distribution of shear failure strength of elements in soil specimens. For the reduction of material parameters, continuum damage mechanics was adopted to simulate the strain-softening behavior and discontinuum mechanics problems of soil. In the model, an element is considered to have failed in the tension mode when its minor principal stress exceeds the tensile strength of the element, or in the shear mode when the shear stress satisfies the modified Mohr–Coulomb failure criterion (F) with a tension cut-off (Brady and Brown, 2004), as shown in Fig. 2.

For the intact element, the potential failure plane should satisfy

$$F = (C' + \sigma' \tan\phi') - \tau$$
$$\sigma_3' \le -\sigma_t' \tag{2}$$

where τ is the shear stress, σ' is the effective normal stress, the difference between the total overburden stress (σ) and a fraction