Laboratory Study of Hydraulic Fracturing in Clay

Etude en Laboratorie sur l'Eclatement Hydraulique des Terrains Argileux

R.A. DECKER Geotechnical Engineer, Law Engineering Testing Company, Houston, Texas, USA
S.P. CLEMENCE Associate Professor, Civil Engineering, Syracuse University, Syracuse, New York, USA

SYNOPSIS A laboratory test technique was developed to study hydraulic fracture initiation in soils. The soil used for the study was a laboratory compacted low plasticity clay. The samples were tested in a standard laboratory triaxial cell with a hypodermic needle implanted in the center of the sample. The internal fluid pressure was increased via the hypodermic needle until hydraulic fracture was initiated in the sample. Onset of fracture was measured by a pore pressure transducer and flow meter. The tests were conducted at various confining pressures to evaluate the effect of external stress level on fracture initiation.

The pressures required to induce fractures in the soil were compared with analytical methods for predicting fracture. It was found that the laboratory results were in close agreement with the Mohr-Coulomb analysis. The results did not compare favorably with Bjerrum's analysis, possibly because of the variation in Poisson's Ratio due to changing stress levels. The testing procedure was found to be a viable method for measuring the tensile strength of a soil under various confining pressure conditions.

INTRODUCTION

The technique of hydraulic fracturing has been used for many years in the mining industry and in grouting processes. Hydraulic fracturing is the formation of cracks in soil or rock due to excessive fluid pressure. Fracturing occurs when the in-situ effective compressive stress is reduced to a negative (tensile) value greater than the tensile strength of the rock or soil. Hydraulic fracturing has recently been applied to soils and has had useful application in determining the in-situ stresses in a soil medium (Bjerrum, et al., 1972 and Penman, 1976).

Hydraulic fracturing is also an important consideration in earth dam design (Nobari, 1973; Kulhawy, 1976). Recent studies (Clemence and Pool, 1977) indicate that hydraulic fracturing may provide a useful application in the excavation and rapid movement of soil masses. A recent literature review completed by Leach (1977) concluded that laboratory tests using the fracturing technique yields an acceptable value of tensile strength for soils and can be used as a property index.

The theoretical and applied basis for hydraulic fracturing is well developed. The purpose of the present study was to investigate the influence of applied stress on the initiation of fracturing under laboratory controlled conditions. The pressures required to induce fracturing were compared with analytical methods for fracture prediction.

SOIL PROPERTIES

The soil used for the tests was obtained from Otisco Valley in New York State. The soil was classified as a CL (Unified Soil Classification System) and has properties as listed in Table 1.

TABLE 1
PROPERTIES OF OTISCO VALLEY CLAY

Percent Sand	2
Percent Silt	60
Percent Clay	38
Liquid Limit (%)	31
Plastic Limit (%)	19
Optimum Water Content (%)	16.7
Maximum Dry Density	18.22 kN/m^3
Unified Soil Classification	CL
Properties of Clay at Maximum Dry Density (Standard Proctor)	
Permeability	5.8×10^{-7} cm/sec
Total Stress Fraction Angle (ϕu)	10.4°
Total Stress Cohesion (c_u)	40.7 k Pa

The samples for the triaxial compression and hydraulic fracturing tests were prepared by statically compacting the soil in a hollow steel cylinder split vertically to allow for easy removal. The soil was prepared at the optimum water content, 16.7%, and compacted to the maximum dry density (Standard Proctor) The mold formed a sample that was 7.12 cm in diameter and 15.24 cm in length.

A series of consolidated undrained (CU) triaxial shear tests were conducted on the statically compacted samples. The samples were end-drained, back pressure saturated and consolidated prior to shearing. The cohesion (c_u) was 40.7 kPa and the measured friction angle (ϕu) was 10.4°.

TESTING EQUIPMENT

The fracturing equipment consisted of a standard triaxial cell, air supply fluid reservoir, pressure transducer, pressure regulator, flow meter and injection needle (Figure 1). The fluid injected into the sample was distilled water which was dyed red to allow for easy detection of leaks within the triaxial cell. The pressure transducer was connected to an electronic recorder so that a record of the pressure application and point of fracture was recorded for each test.

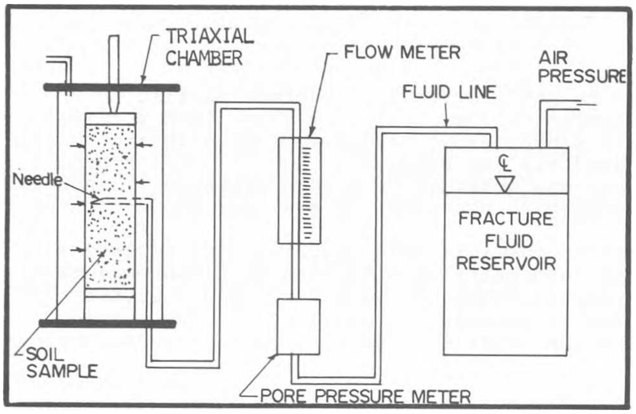

FIGURE 1. Diagram of Hydraulic Fracture Equipment

The injection needle consisted of an esophageal airway needle No. 13 (2.40 mm diam.) which was plugged at the tip. Two 1.01 mm diameter holes were drilled on the circumference of the needle at 180°. The needle was placed in the sample such that the holes were located on the central axes of the sample (Figure 2).

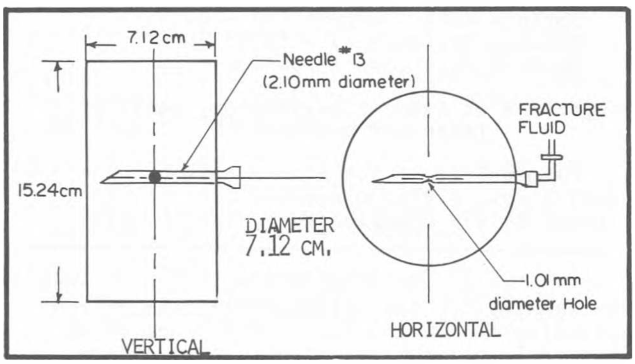

FIGURE 2. Location of Needle in the Soil Sample

TEST PROCEDURES

The soil sample was placed in the triaxial cell and covered with a rubber membrane and at the location where the injection needle was inserted, a small square of rubber membrane was placed between the sample and the enveloping membrane to insure that no leakage would occur when the needle was inserted. As an added precaution, after the needle was inserted approximately 75 percent of the entire length, a layer of silicon lubricant was applied to the needle to act as a grout to help prevent leakage around the needle.

After the needle was in place and the triaxial cell assembled, the sample within the triaxial cell was back pressure saturated and then consolidated at the appropriate confining pressure. When consolidation was complete, the sample was fractured.

The procedure for inducing the fracture started with a uniform increase in pressure in the fluid reservoir which was transmitted to the pressure transducer attached to the electronic recorder and to the injection needle via the flow meter. The flow meter was visually monitored and when the flow showed an abrupt increase, it was determined that fracture had occurred.

The trace from the electronic recorder was inspected and the pressure at which fracture occurred was determined from the drop in pressure in the transducer, which corresponds to the crack development in the sample. The results of the hydraulic fracture tests are shown in Table II.

TABLE II
HYDRAULIC FRACTURE TEST RESULTS

Confining Pressure (σ_3) (kPa)	Fracture Pressure (Δu) Test 1 (kPa)	Test 2 (kPa)	Average (kPa)
34.5	99.3	110.3	104.8
70.0	171.0	172.4	171.7
103.4	227.5	243.4	235.5
137.9	296.5	303.4	300.0

DISCUSSION OF RESULTS

Bjerrum, et al. (1972) developed an analytical solution for hydraulic fracture in soils for various stress conditions and soil properties. For this study, an isotropic stress condition was assumed and soil properties measured in the laboratory were used in the following equation developed by Bjerrum to predict fracture:

$$\Delta u_{ca} = (1-\nu)(P_t' + 2 - \alpha + \beta)(k_o P_o')(S)^{-1} \qquad (1)$$

This equation predicts fracture after the soil has undergone some radial outward strain and Δu_{ca} = pressure at which fracture occurs, ν = Poisson's Ratio, P_t' = tensile strength of soil (usually 0.5 Cu is assumed), α β = factors dependent on soil compressability, k_o = ratio of vertical to horizontal effective stress, P_t' = effective overburden stress and S = shape factor dependent upon radius of needle or piezometer. Predicted values from the Bjerrum analysis using several values of Poisson's Ratio are compared with experimental results as shown in Figure 3. The predicted and measured values do not agree very closely, possibly because of a variation in Poisson's Ratio due to changing stress levels. A linear relationship was found to exist between the pore pressure required to fracture the samples

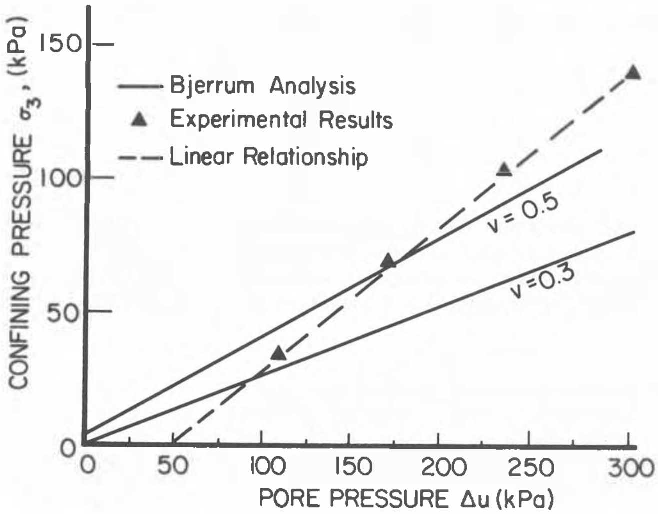

FIGURE 3. Comparison of Average Experimental Test Results and Values Predicted by Bjerrum Analysis

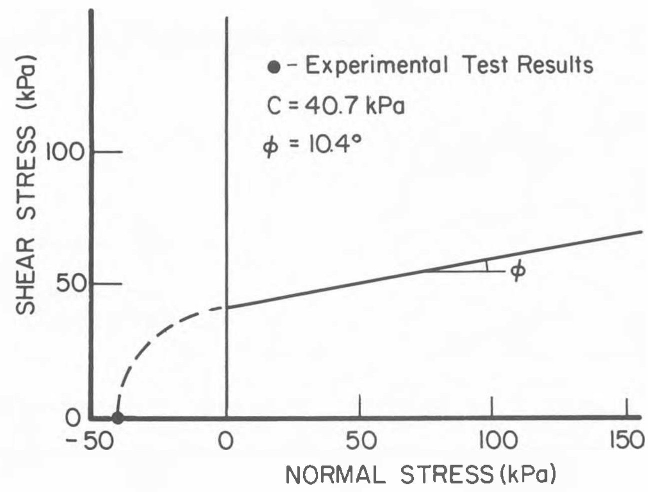

FIGURE 4. Mohr-Coulomb Failure Envelope for Compacted Soil (CU Tests)

and the confining pressure as shown in Figure 3. The line intersects the Δu axis ($\sigma_3 = 0$) at 41.4 kPa. Since the confining pressure is zero, the only restraint acting on the soil to prevent fracturing is the tensile strength. Therefore, Δu to cause fracture must be a measure of the tensile strength of the soil.

Other tests were conducted, including a repetetive fracturing of the same sample. In this repetetive test, the value for fracturing was found to be consistent with the other results until a point was reached where the pressure required to induce fracturing reduced to a value equal to the confining stress. It is postulated that the refracturing must have caused a remolding and saturation of the soil in the vicinity of the crack causing it to lose its tensile strength. However, the pressure required to fracture the sample was equal to the confining stress indicating that the membrane surrounding the soil did not provide any restraint to the soil and the measured value was related only to the soil's tensile strength.

The failure envelope for the compacted soil is shown in Figure 4 with a dashed line in the tensile stress region. Since failure was observed as a crack opening in the samples with no plastic shear occurring, the failure point was plotted as shown in Figure 4. This representation of failure in the tensile stress region is in close agreement with the value that may be predicted from the Mohr-Coulomb analysis.

CONCLUSIONS

1. The tensile strength of a soil can be determined by a series of hydraulic fracture tests as conducted in this study. The experimental equipment developed provides a viable method for inducing hydraulic fracture and measurement of pore pressure required to cause fracture.
2. Experimental results did not compare favorably to results predicted by Bjerrum's analysis possibly because of variation in Poisson's Ratio of the soil influenced by changing stress level.
3. The measured tensile strength was found to be in close agreement with the value that may be predicted from a Mohr Coulomb analysis.

REFERENCES

Bjerrum, L., Nash, K.L., Kennard, R.M. and Gibson, R.E. (1972). Hydraulic Fracturing in Field Permeability Testing. Geotechnique, 22, No. 2, pp. 319-332.

Clemence, S.P. and Pool, J.M. (1977). Strip Mine Reclamation by Induced Slope Failures. Proc. Geotech. Spec. Conf. on Geotechnical Practice for Disposal of Waste Materials, pp. 680-696.

Kulhawy, F.H. and Gurtowski, T.M. (1976). Load Transfer and Hydraulic Fracturing in Zoned Dams, ASCE Jour. of Geotech. Eng., Vol. 102, GT9, Sept., pp. 963-974.

Leach, R.E. (1977). Hydraulic Fracturing of Soils, A Literature Review. U.S. Army Corps of Engrs., Vicksburg, Miss., Misc. Paper, 5-77-6.

Nobari, E.S., Lee, K.L. and Duncan, J.M. Hydraulic Fracturing in Zoned Earth and Rockfill Dams (1973), U.S. Army Corps of Engrs., Vicksburg, Miss., Contract Report 5-73-2.

Penman, A.D. Earth Pressures Measured With Hydraulic Piezometers (1976). Ground Engineering, Vol. 9, No. 8, November, pp. 17-23.