Fissuring from Hydraulic Fracture of Clay Soil

Fissuration des Argiles par Claquage Hydraulique

G. LEFEBVRE Professor, Université de Sherbrooke
A PHILIBERT Graduate Student, Université de Sherbrooke
M. BOZOZUK Division of Building Research, National Research Council of Canada
J-J. PARE Chef de Service, Géologie et Mécanique des Sols, Société d'Energie de la Baie James

SYNOPSIS Hydraulic fracture tests were carried out in two geologically different soft sensitive clays in order to study the fracture pattern which had formed in situ around inserted piezometers. Piezometers of different lengths were used in the test program, and a methylene blue dye was used to mark the fissures. The fractured clay was recovered with a large diameter block sampler and the fissures identified and mapped. Well defined vertical fractures developed around the long piezometer tips but not around the ones of zero length. In all tests, however, fractures inclined from 20 to 35 degrees from the horizontal developed above each piezometer tip, tracing the surface of an inverse cone with its apex at the top of the piezometer.

The paper discusses the fracture patterns and the effects of piezometer length, time of embedment, and the effect of soil disturbance, caused by installing the piezometers, on hydraulic fracture test results.

INTRODUCTION

Hydraulic fracture applied to rock formations is a well known technique that has been used by the petroleum industry for several decades (Le Tirant and Baron, 1979). Its use in cohesive soils to determine lateral stresses in situ is relatively recent (Bjerrum et al, 1972; Bjerrum and Andersen, 1972). The analytical aspects of this technique is based upon the assumptions that the soil is a semi-infinite, homogeneous, isotropic, elasto-plastic mass. Based on these assumptions, Bjerrum et al.(1972) proposed an analytical model to explain what happens in a soil around a piezometer when it is subject to hydraulic fracture.

In the last few years, some questions have been raised concerning the hydraulic fracture test in soft clays with respect to the zone of remoulded soil around the piezometer tip, the direction and extent of the fractures, the degree of homogeneity and natural fissuring (Bozozuk, 1974; Massarsch et al. 1975; Parkin, 1977; Tavenas et al. 1975). The interpretation of the test results was always based on the assumption that hydraulic fracture occurred in a unique and well defined mode. It was never demonstrated that the hydraulic fractures that occurred around a small piezometer tip pushed into a small clay specimen in a laboratory (Bjerrum and Andersen, 1972) were accurate representations of the hydraulic fractures that developed around a full size piezometer in the field, and that the method used to interpret the laboratory test results could be applied directly to the field tests. In the present study hydraulic fracture tests were performed in the field and the fractured clays around the piezometer tips were extracted and examined in order to verify the mode of fracturing in situ. Studies were also made to determine how the estimates of the in situ lateral stresses were affected by heterogeniety of the natural soil, the length of piezometer tips, the remoulding of clay around the piezometer, and the length of time the piezometers were in the ground.

DESCRIPTION OF SOIL DEPOSITS

The tests were performed in two geologically different clay deposits in Eastern Canada at the Gloucester test site near Ottawa, Ontario, and at the Olga test site near Matagami, northwestern Québec.

The soils at Gloucester are marine clay deposits of the Champlain Sea. The geotechnical profile has been described in detail by Bozozuk and Leonards (1972), and by Lo et al. (1976). They are mainly silty clays, almost normally consolidated to a depth of 5,5 m, and lightly overconsolidated to a depth of 18 m where it is underlain by a thin layer of varved clay over till. At the 4 m depth, where the hydraulic fracture tests were performed, the water contents were about 25% greater than the liquid limits, and the sensitivity measured in situ with a Geonor vane varied from 70 to 100. The clay appeared homogeneous in its natural state but displayed a contorted structure when air dried. A summary of the engineering properties of the clay taken around the piezometer tips is given in Table 1.

The soils at Olga are lacustrine deposits of the postglacial lake Barlow-Ojibway. The geotechnical profile has been described in detail by Lefebvre and Locat (1979). The deposit consists of varved clays that are somewhat over-consolidated, and extend to a depth of about 11,5 m at the site. The hydraulic fracture tests were

TABLE I

Summary of Engineering Properties of Soil at the Two Sites

	Olga	Gloucester
Natural Water Content	90%	75%
Liquid Limit	70%	52%
Plasticity Index	40%	25%
Cu (Field Vane)	20 kPa	20 kPa
Sensitivity (Field Vane)	10	70-100
P_c'/P_o'	2,9	1,4
Clay Size Particules (<2μ)	90%	14%

performed at depths of 3,8 and 4,5 m. At these depths the varves alternate between light and dark bands 4 to 10 mm thick. The natural water contents are about 60% for the light and 100% for the dark bands which on the average are about 1,3 times more than the liquid limits. The amount of clay size particles is about 90% and the sensitivity measured in situ with a Nilcon vane apparatus is about 10. A summary of the engineering properties of the soil is given in Table I.

TEST PROCEDURES

Installation of piezometers

Geonor piezometers made of porous bronze and 33 mm in diameter were used. Three lengths were installed: 300 mm (standard), 100 mm and 0 mm. The piezometer tips of 0 length were made from a porous bronze plate. Before installation all piezometer tips and connecting tubing were filled and saturated with deaired water, care being taken to ensure that the tubing was tightly plugged at the top to hold the water and to resist the excess pore water pressures generated during installation. After saturation the piezometer tips were fitted to "E" size steel drill rods (O.D. about 36 mm) and jacked continuously into the ground until the desired depth was attained. Five piezometers were installed to depths of 3,7 to 3,8 m at Gloucester and two to depths of 3,8 and 4,5 m at Olga. The piezometers at Olga were 300 mm long whereas at Gloucester three were 300 mm long (one was a reference piezometer installed in 1972), one was 100 mm long and one had 0 length. The characteristics of the different piezometers and the times of installation and tests are given in Table II.

Hydraulic fracture tests

The tests were performed following the procedure of Bjerrum and Andersen (1972) but instead of using a mercury manometer in the system a pressure transducer was incorporated. Before the tests were performed, however, the water in the piezometers was replaced with an aqueous solution of methylene blue in a concentration of 10 g/L. Methylene blue adheres to the surface of the clay particles and is an excellent tracer for the fractures produced in the test.

The test is performed by gradually increasing the hydraulic pressure in the piezometer using a Geonor screw pump until the soil fractures. The build up of pressure and the subsequent pressure with time as the fractures close is automatically recorded electronically. Initially from 100-300 mL of aqueous solution were injected into the fractures to ensure that sufficient solution was available to mark them, but this was later reduced to 3 mL without loss of definition.

The interpretation of the closing pressure is easily obtained from tests performed in clays of low permeability. In the more permeable clayey silts the closing pressure can be identified from a plot of pressure versus log time (Bozozuk, 1974).

Block sampling of fractured clay

When the hydraulic fracture tests were completed the steel "E" rods and the attached piezometers were rotated to break the bond with the soil, then removed using manual jacks. The hole left in the ground served as a guide for the large diameter block sampler. Two cylindrical undisturbed blocks of clay about 270 mm in diam-

TABLE II

Characteristics and Results of Hydraulic Fracture Tests

PIEZOMETER NO.	LENGTH mm	DATE OF INSTALLATION	DEPTH m	DATE OF TEST	K_o	FRACTURE PATTERN Vertical	Cone
Gloucester test site							
P-43 original	300	72-10-01	3,8	79-09-18	(0,73)	yes	21^o-31^o
P-43 E	300	79-08-28	3,8	79-09-18	(0,68)	yes	35^o
P-43 W	300	79-08-28	3,8	79-09-26	(0,81)	yes	35^oinv.
P-43 (0)	0	79-08-28	3,7	79-09-18	(0,90)	no	16^o-18^o
P-43 (10)	100	79-08-28	3,7	79-09-18	(0,81)	yes	15^o-30^o
Olga test site							
P-19	300	77-06-22	4,5	77-06-27	(1,82)	yes	yes
				79-10-17	(1,39)		
P-28	300	77-06-03	3,8	77-06-27	(2,03)	yes	yes
				79-10-17	(1,46)		

eter and 370 mm long were taken (one above the other) at each piezometer location where the tips were 300 mm long, and only one block obtained where they were 100 and 0 mm long. Each block was carefully wrapped, waxed and shipped in an insulated container to the laboratory. The large diameter block sampler and the sampling technique are described by Lefebvre and Poulin (1979).

MODE OF SOIL FRACTURE

The fractures produced in the clays in the vicinity of the piezometer tips were clearly marked by the methylene blue dye. It was therefore possible to cut selectively the cylindrical blocks of soil into sections and precisely map the network of fractures. These are shown graphically for the soil around piezometers P-43 (0), P-43(10) and P-43E from the Gloucester site (respectively 0, 100 and 300 mm long) on Figs 1 and 2. Figure 1 shows the fractures that appeared on the outside of the cylindrical blocks while Figure 2 shows them on selected horizontal sections after the blocks were cut. Similar observations were made on the block samples from the Olga site, but the fractures were not as clearly defined because of alignment difficulties during sampling.

The fracture mode was quite different from the one assumed for interpreting hydraulic fracture tests in clay soils. Large, well-defined, vertical fissures were observed on the block of soil surrounding the 300 mm long piezometer tip (Fig. 1(c)), which extended radially outward from the hole left by the piezometer (Fig. 2 Section CD). As the piezometer tip became shorter (100 mm), the fissures on the outside of the block became shorter and subvertical (Fig. 1 (b)), and they also radiated outward from the hole left by the piezometer (Fig. 2, Section BB). When the length was reduced to 0, vertical fissures were almost entirely absent (Fig. 1 (a), Fig. 2, Section AA).

In addition to the vertical fractures, however, a well-defined continuous fracture appeared on all the blocks of soil at a location above the head of the piezometer. These fractures occurred at an angle varying from 20 to 35 degrees from the horizontal, tracing a curved surface forming an inverted cone (Fig. 1(a), 1(b), 1(c)). This cone was particularly well defined in the soil around the piezometer tip of 0 length. Figure 2 shows the pattern of concentric fractures from this cone that formed above each of the piezometer tips (Sections AA, BA and CA).

Figure 3 was prepared from the observed distribution of fractures to show the fracture mode

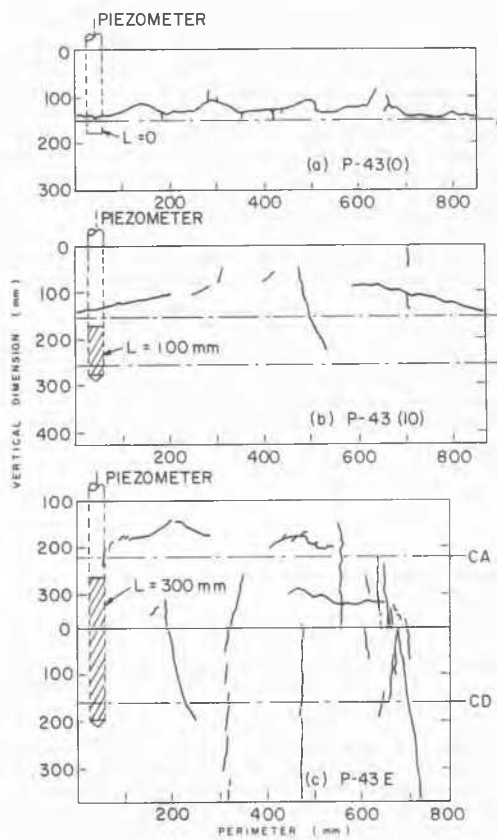

Fig. 1 Fractures identified at the vertical periphery of the samples

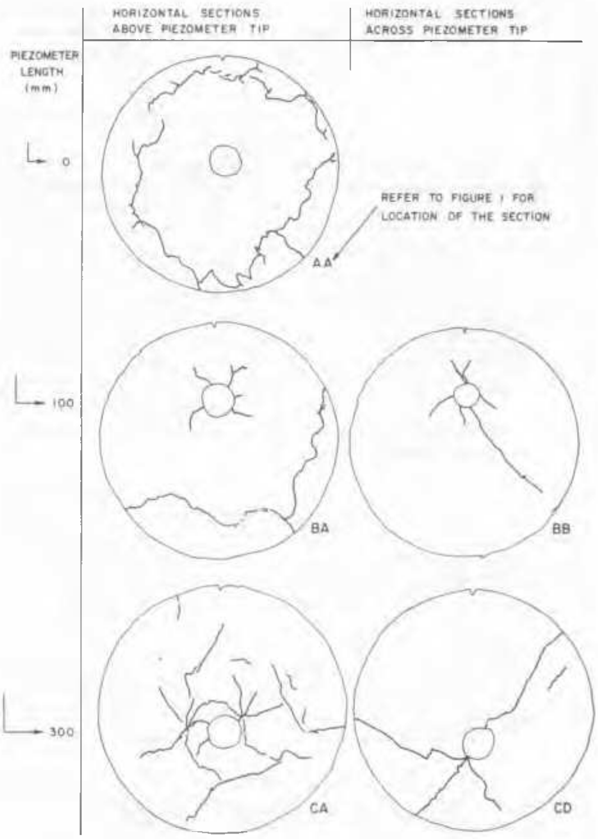

Fig. 2 Fractures identified on horizontal cross-sections for different lengths of piezometer tips

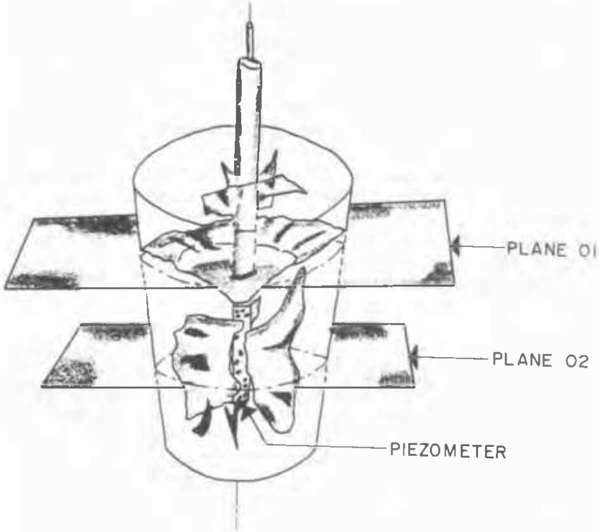

Fig. 3 Schematical representation of the fractures observed around the piezometer tip.

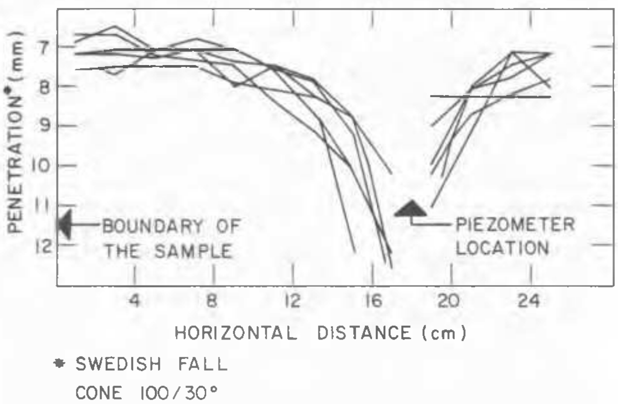

Fig. 4 Swedish fall cone penetration around piezometer tip.

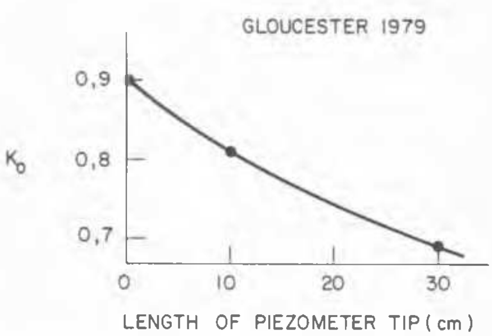

Fig. 5 Influence of the length of piezometer tip on the calculated value of K_o.

that develops in the clay around a piezometer of some length as a result of an hydraulic fracture test. There are two distinct fracture zones. A continuous crack forms at the top of the piezometer tip forming the surface of an inverted cone with its apex at the piezometer. The angle of the cone varies from 20 to 35 degrees from the horizontal and increases with the length of piezometer tip. The intersection of plane 01 with the surface of the cone (Fig. 3) traces cracks which are similar to those shown on Fig. 2 (Sections AA, BA and CA).

The second fracture zone contains essentially vertical (and subvertical) fractures radiating outward from the piezometer tip (Fig. 3). The number of fractures and the angle between them are variable and not unique. The trace left by the fractures intersecting plane 02 (Fig. 3) is similar to the ones observed on Fig. 2 (Sections BB and CD).

SOIL DISTURBANCE AROUND THE PIEZOMETER TIPS

Soil disturbance or remoulding caused by installing the piezometer has often been used to explain questionable test results. It was possible in the present study to verify the extent of remoulding and to evaluate its influence on the mode of fracture in the hydraulic fracture test. Tests with a Swedish cone penetrometer were carried out on each of the slices cut from the large block samples. The penetration indices showed that the disturbed zone extended horizontally for a distance of 2 to 3 piezometer diameters (Fig. 4). Some of this disturbance occurred at the time of installation, but most of it probably took place after the tests were completed when the piezometers were rotated and pulled out. This zone was generally less important for the less plastic (I_p = 25%), extremely sensitive (S_t = 70-100) clays at Gloucester than for the clays at Olga where the plasticity was higher (I_p = 40%) and the sensitivity less (S_t = 10).

The development of radial fractures around the piezometer tips did not seem to be affected by the presence of the disturbed zone of soil. The fractures developed and passed through the disturbed zone and extended into the undisturbed neighbouring clay as indicated on Fig.2, Sections BB and CD.

EFFECT OF FRACTURE MODE ON K_o

The value of K_o, calculated from hydraulic fracture tests is affected by the length of piezometer tip as shown on Fig. 5. Using the 300 mm long piezometer tip, a K_o of 0,68 was obtained. It increased to 0,81 using the 100 mm long tip, and finally a value of 0,91 was measured using the piezometer of 0 length. The variation must be due to the fracture mode observed around the piezometer tips. The 300 mm long tip produced the longest vertical fractures, and it could be argued that this test was mostly influenced by the horizontal pressure in the soil. The 100 mm long tip produced shorter vertical and subvertical fractures. The fact that K_o increased to 0,81 shows that the test is also sensitive to the inclined fractures which formed at the head of the piezometer, and that it is responding more to the vertical pressure. There were no vertical fractures around the piezometer of 0 length, and it gave a K_o = 0,91. The fractures were inclined forming an inverted cone. Consequently the pressures measured in this test were strongly influenced by the vertical overburden pressure, and to a minor extent by the horizontal pressure.

The inverted fracture cone was observed to develop above all piezometer tips in all tests, and consequently all determinations of K_o were affected. It could be argued that the best results were obtained using the 300-mm-long piezometer tips, but the correct K_o is still not known.

REDUCTION OF MEASURED K_o WITH TIME

Hydraulic fracture tests were performed on an interval of 28 months on the piezometers at Olga. There was a marked reduction in the stress ratio K_o over this time period, by as much as 24 and 28% for piezometers P-19 and P-28 respectively as shown in Table 2. This agrees with Tavenas et al. (1975) who also found that long relaxation times produced a significant reduction in measured horizontal pressure. This reduction can be attributed to soil relaxation around the piezometer tip (consolidation and creep). It is very likely, however, that the vertical fractures that formed perpendicular to the smallest stresses (horizontal) in the first test were enlarged by repeated hydraulic fracture tests. Consequently subsequent tests would be more sensitive with time to the smaller horizontal pressures. On the other hand, the cone-shaped fracture plane at the head of the piezometer tip is sensitive to the greater vertical pressures and it would not be affected by repeated tests to the same degree.

DISCUSSION

The fractures formed in the clay soils from the hydraulic fracture tests were easily marked and identified using the methylene blue dye. Fractures that formed during the tests are not only related to the horizontal pressures, but also to the vertical pressure.

The fracture cone observed at the head of piezometer P-43W (Table 2) sloped downwards and limited the length of the vertical fractures which developed around the piezometer tip. Consequently the vertical stress had a greater influence during the test, and this increased the measured K_o to 0,81 from 0,68 obtained with P-43E (Table II).

Sampling difficulties were encountered at Olga. The large block samples that were recovered almost missed the fractured zone around the piezometer tips. The very little information that was obtained showed that the fracture mode was similar to that observed in the marine clay at Gloucester. The varved clay at Olga appeared to have little or no influence on the development of fractures during the tests.

CONCLUSIONS

Seven hydraulic fracture tests performed in two soft clay deposits of different geologic origin have shown that the fracture mode is not unique. Two distinct sets of fractures developed. Vertical fractures radiated out from the piezometer tips as expected and, in addition, cracks inclined from 20 to 35 degrees from the horizontal formed an inverted cone-shaped fracture surface with its apex at the top of the piezometer. As the hydraulic fracture test would be sensitive to the fluid pressures in both sets of fractures it would lead to an overestimate of K_o. The hypothesis that a unique fracture mode, i.e., that only vertical fractures developed in normally consolidated clay, was not verified.

The presence of the remoulded or disturbed soil around the piezometer tips did not affect the development of fractures during the hydraulic fracture tests.

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REFERENCES

Bjerrum, L., Andersen, K.H. (1972). In situ Measurement of Lateral Pressures in Clay, Proceedings of the 5th European Conf. of the I.S.S.M.F.E., Madrid, Vol. 1, pp. 11-20.

Bjerrum, L., Nash, J.K.T.L., Kennard, R.N., Gibson, R.E. (1972). Hydraulic Fracturing in Field Permeability Testing, Géotechnique, vol. 22, no 2, pp. 319-332.

Bozozuk, M. and Leonards, G.A. (1972). The Gloucester Test Fill. Proc. ASCE Specialty Conference on Performance of Earth and Earth-Supported Structures, Purdue University, 11-14 June, Vol. 1, Part 1, pp. 299-317.

Bozozuk, M. (1974). Minor Principal Stress Measurement in Marine Clay with Hydraulic Fracture Tests, presented at the Engineering Foundation Conference on Subsurface Exploration for Underground Excavation and Heavy Construction, New England College, Henniker, New Hampshire, pp. 333-349.

Le Tirant, P. et Baron, G. (1970). Fracturation hydraulique des roches stratifiées et fissurées - Application aux réservoirs d'hydro-carbures. Compte rendu du 2e Congrès de la Société internationale de mécanique des roches, Belgrade, 1970, Vol. 3.

Lefebvre, G., Poulin, C. (1979), A New Method of Sampling in Sensitive Clay, Canadian Geotechnical Journal, Vol. 16, No 1, pp. 226-233.

Lefebvre, G., Locat, J., Paré, J.-J. and Dascal, O. (1979). A Detailed Study of the Compressibility of a Varved Clay Deposit as Related to Foundation Settlement, 32nd Canadian Geotechnical Conference, Quebec, Canada.

Lo, K.Y., Bozozuk, M., Law, K.T. (1976). Settlement Analysis of the Gloucester Test Fill, Canadian Geotechnical Journal, Vol. 13, no 4, pp. 334-354.

Massarsch, K.R., Holtz, D.L., Holm, B.G. and Fredriksson, A. (1975). Measurement of Horizontal In Situ Stresses, ASCE, Specialty Conference on In Situ Measurements of Soil Properties, Raleigh, N.C., Vol. 1, pp. 266-286.

Parkin, A.K. (1977). Lateral Earth Pressure at Rest in Soft Clay, Discussion, Journal of the Geotechnical Engineering Division, A.S.C.E., Vol. 103, GT9, pp. 1030-1031.

Tavenas, F., Blanchette, G., Leroueil, S., Roy, M., La Rochelle, P. (1975). Difficulties in the In Situ Determination of K_o in Soft Sensitive Clays. Proceedings of the ASCE Specialty Conference on In Situ Measurement of Soil Properties, Raleigh, N.C., pp. 450-476.