INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

SIMSG ISSMGE

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

XIII ICSMFE, 1994, New Delhi, India / XIII CIMSTF, 1994, New Delhi, Inde

UNDRAINED HYDRAULIC FRACTURE IN CAVITY EXPANSION TESTS

FRACTURE HYDRAULIQUE NON DRAINEE DANS LES ESSAIS D'EXPANSION DE LA CAVITE

J.H. Atkinson[1] ***J.A. Charles***[2] ***H.K. Mhach***[3]

[1]City University, London, U.K.
[2]Building Research Establishment, Watford, U.K.
[3]Sir Alexander Gibb and Partners, Reading, U.K.

SYNOPSIS: Hydraulic fracture is often an initiatory mechanism in the development of concentrated leakage and internal erosion in clay cores of embankment dams. The conditions under which fracture occurs are not well understood and a programme of laboratory tests has been carried out to investigate the phenomenon. Samples with a central cylindrical cavity were tested in a hydraulic triaxial cell by quickly raising fluid pressure inside the cavity until hydraulic fracture occurred. The hydraulic fracturing pressure has been related to the confining pressure, the undrained shear strength of the soil and the ratio of the diameter of the cavity to the diameter of the sample. The effect on the fracturing pressure of several other factors has been examined including the type of pressurising fluid, the over-consolidation ratio, the initial stress ratio and raising the cavity pressure relatively slowly so that the loading was no longer fully undrained. The significance of the work for the rapid filling of a reservoir is discussed.

INTRODUCTION

There is extensive field evidence that hydraulic fracture is often an initiatory mechanism in the development of concentrated leakage and internal erosion in clay cores of embankment dams (Sherard, 1985). There are many examples of modern embankment dams where leakage and internal erosion have been attributed to hydraulic fracture including Balderhead Dam in England, Hyttejuvet Dam in Norway, Viddalsvatn Dam also in Norway, Teton Dam in the United States of America and Stenkullafors Dam in Sweden. In the case of Teton the dam failed catastrophically soon after the leakage was detected.

Although hydraulic fracture is widely recognised as a potential hazard to the satisfactory performance and safety of embankment dams, the conditions under which it occurs are not well understood. A number of field investigations, laboratory test programmes and theoretical studies have been reported (Bjerrum et al, 1972; Nobari et al, 1973; Decker and Clemence, 1981; Penman and Charles, 1981; Jaworski et al, 1981; Lefebvre et al, 1981; Hassani et al, 1985; Mori and Tamura, 1987; Charles and Watts, 1987; Panah and Yanagisawa, 1989; Tam et al, 1988; Lo and Kaniaru, 1990). A laboratory investigation has been carried out to establish the conditions under which undrained hydraulic fracture occurs and from these tests hydraulic fracture pressure has been correlated to the confining pressure, the undrained strength of the soil and the sample geometry. A linked item of research examined whether there were significant differences in erosion resistance between the different types of clay that have been used in British embankment dams (Atkinson et al, 1990).

LABORATORY TESTS

A series of laboratory tests was carried out in which hydraulic fracturing was caused by rapid increase of fluid pressure in cavities in triaxial samples. The apparatus is shown diagrammatically in Fig 1. A cylindrical sample in a thin rubber membrane is contained in a conventional hydraulic triaxial cell (Bishop and Wesley, 1975) in which unequal axial and radial stresses can be held constant. Pore pressures in the sample are controlled through drainage leads in the base pedestal. The sample contains a cylindrical cavity formed by drilling a hole with a thin tube. A short length of the cavity is filled with coarse sand and the remainder is plugged with a metal cylinder. A thin tube passes through the metal cylinder into the sand pocket and this is connected through the top platen to a pressure control valve and a conventional volume gauge. The sizes of the samples were 38mm or 100mm dia. The cavities were 6mm, 16mm or 38mm dia and generally 25mm long so the geometry was intermediate between a hollow cylinder and a hollow sphere.

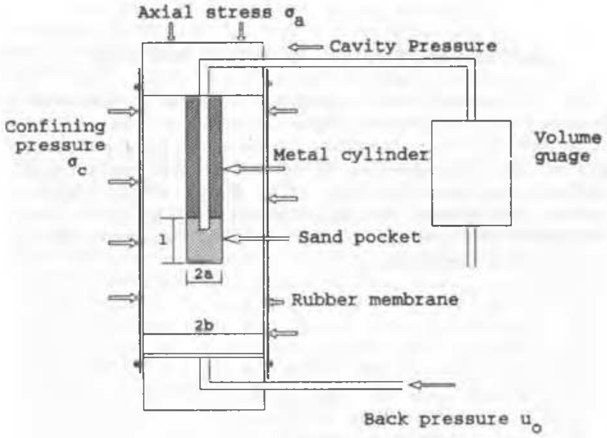

Fig 1 Test Sample

The material used in the tests was a clay (w_L - 42%, w_P - 18%) obtained from the core of an old dam in Wales. The samples were reconstituted to a slurry and reconsolidated in a simple long oedometer. After consolidation to render the samples sufficiently strong to handle, the central cavity was formed by coring and they were then installed in the hydraulic triaxial cell where they were further consolidated to the required initial state. The initial state was slightly anisotropic with $\sigma_a = \sigma_c \pm 20$kPa. where σ_a is the axial stress and σ_c is the lateral confining pressure and with a back pressure u_0 in the range approximately 10 to 400kPa.

When a sample was in equilibrium with the total stresses and pore pressures, the fluid pressure in the sand-filled cavity was quickly raised. The time to failure was generally in the range 1 to 10 min but in a few tests the cavity pressure was raised slowly over periods of several hours to examine the change of fracture pressure with partial drainage. In the majority of tests the fluid in the cavity was water but in a few tests paraffin was used to ensure that the fracturing was fully undrained. In all the quick undrained tests the volume gauge registered negligible volume changes until hydraulic fracture occurred when there was a sudden flow through the volume gauge. The flow into the cavity and through the fracture caused the membrane to expand and this was stopped by rapidly closing a valve in the supply lead.

A preliminary series of conventional consolidated undrained triaxial compression and extension tests was carried out to establish the relationship between undrained strength s_u, consolidation pressure and time to failure. The value of undrained strength used later to examine the results of the hydraulic fracture tests was taken as the mean of the values corresponding to failure in compression and extension at the particular consolidation pressure taking account of the time to failure.

SIMPLE ANALYSIS OF UNDRAINED HYDRAULIC FRACTURE

If it is assumed that undrained hydraulic fracture is governed by the undrained shear strength of the soil close to the cavity it is possible to develop simple solutions based on the distribution of stress around cylindrical or spherical cavities (De Moor 1989, Mhach 1991). With the stresses and dimensions illustrated in Fig 2, σ_f is the pressure in the cavity at the instant of fracture and σ_c is the confining pressure.

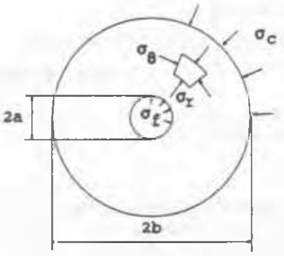

Fig 2 Stresses in a hollow cylinder and a hollow sphere

With $\sigma_r - \sigma_\theta = 2s_u$ at r = a at the cavity wall the solutions for a cylindrical and a spherical cavity are, respectively

$$\frac{\sigma_f - \sigma_c}{s_u} = (1 - \frac{a^2}{b^2}) \qquad (1)$$

$$\frac{\sigma_f - \sigma_c}{s_u} = \frac{4}{3}(1 - \frac{a^3}{b^3}) \qquad (2)$$

Eqns 1 and 2 can be written in the form

$$\frac{\sigma_f - \sigma_c}{s_u} = N_f \qquad (3)$$

where N_f is an undrained fracture factor which depends on the geometry given by a/b. (N_f is analogous to the undrained bearing capacity factor N_c)

LABORATORY TEST RESULTS

In all the tests hydraulic fracture was a well defined event characterised by the start of flow through the volume gauge. On completion of a test when the samples were removed from the apparatus cracks could be seen which became very clear as the sample was allowed to dry naturally. The orientation of the cracks was normal to the direction of the minor principal stress (ie. for $\sigma_c < \sigma_a$ they were vertical and radial while for $\sigma_a < \sigma_c$ they were horizontal).

After the initial hydraulic fracture had occurred flow through the volume gauge could be stopped and restarted by lowering and raising the cavity pressure indicating that the initial fracture could be made to open and close. The cavity pressure at which the flow stopped and restarted was initially very close to the minor principal stress but after a delay the closure and refracture pressure increased although the initial fracture pressure was never fully recovered.

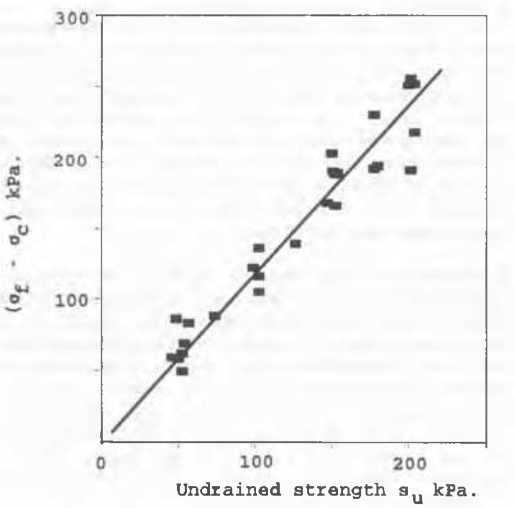

Fig 3 Fracture of normally consolidated samples

Fig 3 shows the variation of $(\sigma_f - \sigma_c)$ with undrained strength s_u for 38mm dia samples with a/b = 0.16. The samples were all normally consolidated; they had different values of effective consolidation pressure and undrained strength and include tests with σ_a either larger or smaller than σ_c. They include tests with paraffin and tests with water in the central cavity. The data fall close to a line given by $N_f = 1.25$ where N_f is the undrained fracture factor defined by eqn 3. For a/b = 0.16 eqns 1 and 2 give N_f = 1.0 and 1.33 respectively. The geometry of the sample and cavity in Fig 1 is intermediate between a hollow cylinder and a hollow sphere and so the test results are in good agreement with the analysis which assumes that fracture occurs when s_u is first mobilised at the cavity wall.

Table 1. Summary of hydraulic fracture tests

Test series	a (mm)	b (mm)	a/b	State
○	3	19	0.16	NC
○	8	50	0.16	NC
□	3	50	0.06	NC
■	8	19	0.42	NC
△	8	19	0.42	OC

Tests were also carried out on 38mm and 100mm diameter samples with a/b in the range 0.06 to 0.42 and on overconsolidated samples with overconsolidation ratios up to 12 (see Table 1). In each series of tests there was a linear relationship between $(\sigma_f - \sigma_c)$ and s_u and the values of N_f obtained from the slopes of the lines are shown in Fig 4. Also shown in Fig 4 are the relationships between N_f and a/b given by eqns 1 and 2 over the complete range from 0 corresponding to a negligibly small cavity to 1 corresponding to a negligibly thin cylinder. (Note that for a/b < 0.3 the value of $N_f = 1.33$ is approximately constant.)

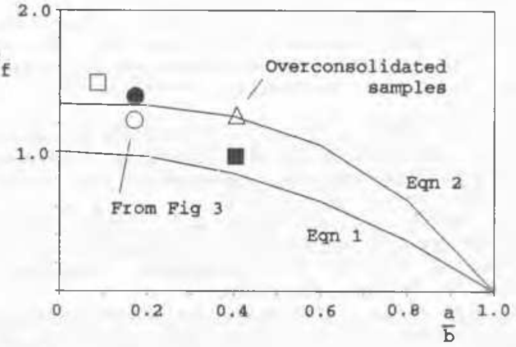

Fig 4 Variation of fracture factor with geometry

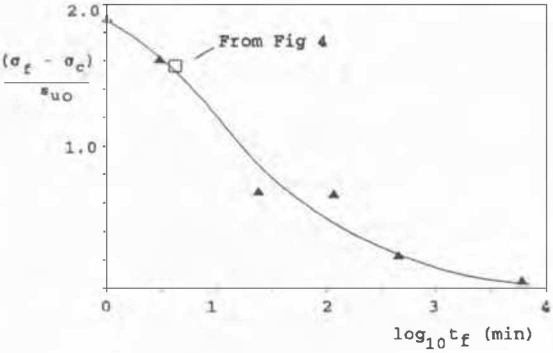

Fig 5 Variation of fracture factor with time to failure

Fig 5 shows values of N_f obtained from a series of tests on normally consolidated samples with a = 3mm and b = 50mm in which the time to failure was varied from 1 min to about 3 days. (The data are plotted as $(\sigma_f - \sigma_c)/ s_{uo}$ where s_{uo} is the initial undrained strength.) The data show how the fracture pressure decreases with increasing time as the conditions are no longer undrained. For very long times when the loading is nearly fully drained the fracture pressure is approximately equal to the confining pressure. For very rapid loading the fracture pressure increases above the values in Fig 4 probably because the undrained strength increases for very high rates of strain.

Some similar laboratory testing programmes have been reported. A detailed comparison of results is difficult because of differences in sample preparation and testing techniques and in some cases insufficient data are presented. Hassani et al (1985), Mori and Tamura (1987) and Panah and Yanagisawa (1989) carried out hollow cylinder tests, whereas the test configuration used by Lo and Kaniaru (1990) was closer to that used in the investigation reported in this paper. Hassani et al (1985) found that partially saturated samples required higher fracturing pressures than saturated samples and that samples compacted dry of optimum moisture content had higher fracturing pressures than those compacted wet of optimum. Mori and Tamura (1987) carried out tests on six types of fine grained soil and concluded that shear failure near the borehole rather than tensile failure initiated hydraulic fracture. Panah and Yanagisawa (1989) also concluded that hydraulic fracturing was initiated by shear failure near the borehole. If $\phi_u = 0$ is substituted in their expression for hydraulic fracturing pressure, it reduces to our equation 1. Lo and Kaniaru (1990) used three test procedures involving samples which were respectively, unsaturated unconsolidated (UU), saturated consolidated (SC) and saturated unconsolidated (SU). Each test series showed that the fracturing pressure was a linear function of confining pressure; the SC tests showing the largest fracturing pressures and the SU tests the lowest. The expression presented for fracturing pressure included the tensile strength of the soil. All these investigations showed that hydraulic fracturing pressure was a linear function of confining pressure.

HYDRAULIC FRACTURE IN EMBANKMENT DAMS

Hydraulic fracture may occur within a core due to excess water pressure in a borehole or piezometer. This has been used as a method of in situ stress measurement and has also happened inadvertently during drilling in cores. Providing that the volume of water is small, there should be no deleterious effect on the core. The clay core of an embankment dam may be fractured by the reservoir water pressure acting on its upstream face and this can lead to internal erosion. The significance of the laboratory test programme needs to be assessed for both these situations.

Hydraulic fracture in a borehole or piezometer is closely related to the laboratory tests as the geometry is usually similar. As the borehole or piezometer will be small compared with the dimensions of the core, the field situation corresponds to a/b ≈ 0. The laboratory tests indicate that the magnitude of the minor principal stress will be overestimated by about $1.3s_u$ in a test which is carried out reasonably quickly.

The relationship between hydraulic fracture of the core due to the reservoir pressure and the laboratory tests is less certain. The geometry is very different although the field situation could be likened to the laboratory case with a/b = 1. The major difference is that whereas the pressure in the cavity in the laboratory test is localised within a relatively large sample, the reservoir pressure acts on the whole of the upstream face of the core and has a controlling effect on the stress state throughout a narrow central clay core. This means that care is needed in applying the laboratory results to the field situation. For example the laboratory results show that increasing the rate at which the cavity pressure is raised increases the fracturing pressure and it might be concluded from this that very rapid filling of a reservoir would reduce vulnerability to hydraulic fracture. However any helpgained by rapid application of the fracture pressure may be lost if the pressure is then maintained as would normally be the case with reservoir filling. More importantly finite element studies have shown that the stress conditions after undrained impounding are more adverse than that after drained impounding (Dounias et al, 1989). Vaughan (1987) suggested that rapid impounding is likely to be more hazardous than slow impounding since there is less opportunity for stress redistribution to occur.

A prolonged major drawdown of a reservoir will substantially increase effective stresses and hence undrained strength in the core. Although on reservoir refilling the water content will be increased the original pre-drawdown water contents will not be fully recovered and some of the increase in undrained strength will remain. The laboratory tests have indicated that an increase in undrained strength improves resistance to hydraulic fracture and this helps to explain why hydraulic fracture is often most likely to occur during the first impounding of a reservoir.

In practice a clay core will not be entirely homogeneous and the boundary between the clay core and the upstream fill will not be perfectly regular and smooth. It has been suggested that more permeable layers within the core and irregularities in the core-fill boundary could have an important effect on the initiation of hydraulic fracture (Vaughan, 1987; Lofquist, 1992). However Mori and Tamura (1987) found that a pre-existing wedge formed by a steel wire had little effect on the cavity fracture pressure measured in undrained tests. The question of the mechanism of hydraulic fracture in dam cores remains to be fully resolved.

ACKNOWLEDGEMENTS

The work describes in this paper was carried out while the third author was supported by an SERC Case award held in collaboration with the Building Research Establishment.

REFERENCES

Atkinson, J.H., Charles, J.A. and Mhach, H.K. (1990). Examination of erosion resistance of clays in embankment dams. Quarterly Journal of Engineering Geology, Vol. 23. pp. 103-108.

Bishop, A.W., Wesley, L.D. (1975). A Hydraulic Triaxial Apparatus for controlled stress path testing. Géotechnique, Vol. 25, pp. 657-670.

Bjerrum, L., Nash, J.K.T.L., Kennard, R.M. and Gibson, R. E. (1972). Hydraulic fracturing in field permeability testing. Geotechnique, Vol. 22, pp. 319-332.

Charles, J.A. and Watts, K.S. (1987). The measurement and significance of horizontal earth pressures in the puddled clay cores of old earth dams. Proceedings of Institution of Civil Engineers, Part 1, Vol. 82, Feb, pp. 123-152.

Decker, R.A. and Clemence, S.P. (1981). Laboratory study of hydraulic fracturing in clay. Proceedings of 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, Vol. 1, pp. 573-575.

De Moor, E.K. (1989). Modelling of Deep Tunnel Behaviour in Clay. PhD Thesis, City University.

Dounias, G.T., Potts, D.M. and Vaughan, P.R. (1989). Numerical stress analysis of progressive failure and cracking in embankment dams. Department of Environment Contract no PECD 7/7/222.

Hassani, A.W., Singh, B., Saini, S.S. and Goel, M.C. (1985). Laboratory simulation of hydraulic fracturing. Proceedings of 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, Vol. 2, pp. 1081-1084.

Jaworski, G.W., Duncan, J.M. and Seed, H.B. (1981). Laboratory study of hydraulic fracturing. ASCE Journal of Geotechnical Engineering Division, Vol. 107, No GT. 6, pp. 713-732.

Lefebvre, G., Philibert, A., Bozozuk, M. and Pare, J.J. (1981). Fissuring from hydraulic fracture of clay soil. Proceedings of 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, Vol. 1, pp. 513-518.

Lo, K.Y., and Kaniaru, K. (1990). Hydraulic fracture in earth and rockfill dams. Canadian Geotechnical Journal, Vol. 27, pp. 496-506.

Lofquist. B, (1992). Hydraulic penetration in embankment dams. Ground Engineering, June, pp. 40-43.

Mhach, H.K. (1991). An Experimental Study of Hydraulic Fracture and Erosion. PhD Thesis, City University.

Mori, A. and Tamura, M. (1987). Hydrofracturing pressure of cohesive soils. Soils and Foundations, Vol. 27, No. 1, pp. 14-22.

Nobari, E.S., Lee, K.L. and Duncan, J.M. (1973). Hydraulic fracturing in zoned earth and rockfill dams. Contract Report S-73-2, US Army Engineers Waterways Experiment Station, Vicksburg, Mississippi.

Panah, A.K. and Yanagisawa, E. (1989). Laboratory studies on hydraulic fracturing criteria in soil. Soils and Foundations, Vol. 29, No. 4, pp. 14-22.

Penman, A.D.M. and Charles, J.A. (1981). Assessing the risk of hydraulic fracture in dam cores. Proceedings of 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, Vol. 1, pp. 457-462.

Sherard, J.L. (1985). Hydraulic fracturing in embankment dams. Proceedings of ASCE Symposium on Seepage and Leakage from Dams and Impoundments (ed. Volpe and Kelly), Denver, pp. 115-141.

Tam, H-K., Mhach, H.K. and Woods, R.I. (1988). Numerical investigation of hydraulic fracturing in clays. Numerical Methods in Geomechanics, Innsbruck, pp. 563-570, Balkema, Rotterdam.

Vaughan, P.R. (1987). Discussion on the measurement and significance of horizontal earth pressures in the puddle clay cores of old earth dams. Proceedings of Institution of Civil Engineers, Part 1, Vol. 82, December, pp. 1249-1255.