

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



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.

The paper was published in the proceedings of the 7th Australia New Zealand Conference on Geomechanics and was edited by M.B. Jaksa, W.S. Kaggwa and D.A. Cameron. The conference was held in Adelaide, Australia, 1-5 July 1996.

Hydraulic Fracturing In Embankment Dams: A Tension Failure Mechanism

C.H. de A.C. Medeiros

Ph.D., M.Sc., C.Eng.

Senior Lecturer, Universidade Estadual de Feira de Santana, Brazil

A.I.B. Moffat

RD, B.Sc., C.Eng., MICE, FGS, DL

Senior Lecturer, University of Newcastle, United Kingdom

Summary This paper describes a novel test procedure for the experimental study of hydraulic fracturing carried out on a PFA-based artificial 'soil'. The technique was based on use of a 250 mm Rowe consolidation cell to contain a hollow cylindrical, i.e. annular specimen. The role played by the tensile strength of the soil was considered in the tests, contrasting with the majority of investigations where it was assumed that either zero or was negligible. The split cylinder test, otherwise known as the Brazilian Test, was used to determine the tensile strength of the soil.

1. INTRODUCTION

The term hydraulic fracturing has been used in the literature to denote: the fracture of an intact mass of soil, and the opening of a pre-existing crack within, or through the soil mass. The mechanism of hydraulic fracturing (i.e., the generation of cracks in soils or rocks due to excessive internal fluid pressure), however, is not well understood. It is generally accepted that a tensile effective stress is required.

Prompted by the findings that shear failure rather than tensile failure was assumed to be responsible for the initiation of hydraulic fracturing in cohesive soils [Mori and Tamura, 1987 and Panah and Yanagisawa, 1989], the question of whether hydraulic fracturing is a shear or tension failure mechanism was investigated.

It was concluded that hydraulic fracturing is a tension failure mechanism. The test results obtained were analysed using stress-path diagrams. In all hydraulic fracturing tests a tension failure was observed. This was confirmed by stress-path plots in terms of the hoop stresses.

2. SOIL TESTED

The soil tested was an artificial 'soil'. A laboratory testing programme was established to examine the basic engineering properties of two different batches of Pulverised Fuel Ash (PFA), and of PFA combined with Supreme Powder China Clay (SPCC) kaolin. Pure PFA is a non-plastic

material, and a quantity of SPCC was added to lend plasticity. The mix 85% PFA and 15% SPCC (85PFA2) was intended to conform broadly to the plasticity and grain-size distribution characteristic of the core material of the Teton Dam

2.1 Soil Properties

The mixture 85PFA2 ($w_L = 31.5-33.5\%$, $w_P = 24 - 25.5\%$ and $I_P = 6 - 9.5$) matched the selection criteria of conformity to Teton silty core material. The PFA fraction with a grain size of more than 2.0 mm was removed. The components (PFA and SPCC) were thoroughly inter mixed dry and statically compacted to two controlling target conditions: i) $\rho_d = 1.42 \text{ Mg/m}^3$, $w\% = 15.9\%$ (-2% OMC) and, ii) $\rho_d = 1.42 \text{ Mg/m}^3$, $w\% = 19.9\%$ (+2% OMC).

2.2 Tensile Strength Tests: Brazilian Method

The split cylinder test, otherwise known as the Brazilian Test, was used to determine the tensile strength, σ_t , of the 85PFA2 mixture. This test was first developed to measure the tensile strength of concrete [Carneiro and Barcellos, 1953]. Some criticism surrounds its applicability to soils, but it has been adopted by several investigators due to its relative simplicity [Hassani et alii, 1985; Seco e Pinto, 1983; Lo and Kaniaru, 1990]. The magnitude of tensile strength of the soil, σ_t can be obtained using the equation:

$$\sigma_t = \frac{2P}{\pi DL} \times 100 \text{ (kPa)} \quad (1)$$

where,

- σ_t is the tensile strength of the specimen, kPa
- P is the applied load, N
- D is the diameter of the specimen, cm
- L is the length of the specimen (cylinder), cm

A series of eighteen samples, 72 mm diameter and 36 mm in length was tested. The tensile strength of the 85PFA2 mixture was found to be $\sigma_t = 10.51 \pm 1.30$ kPa for samples compacted at OMC+2%, $\sigma_t = 17.27 \pm 1.60$ kPa for samples compacted at OMC, and $\sigma_t = 21.73 \pm 0.91$ kPa for samples compacted at OMC-2%. These values were subsequently used in further calculations.

3. THE HYDRAULIC FRACTURING TEST

3.1 The HF-Test Apparatus

The experimental arrangement used for the hydraulic fracturing tests consists essentially of a 250 mm Rowe consolidation cell (Rowe and Barden, 1966) connected to a volume-change device. A photographic view of the experiment can be seen in Figure 1. The Rowe cell was adapted to apply three independently identified pressures.

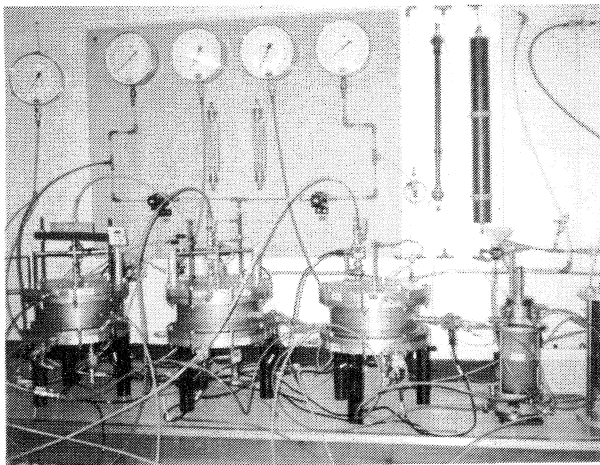


Figure 1. General view of the Rowe cells, prepared for a sequential hydraulic fracturing test.

A primary advantage of the Rowe cell technique lies in its flexibility. The hydraulic fracturing mechanism can be better modelled to give a fresh insight into the basics of the problem. From this, combined with the very important feature that the tests are carried out under 'partially drained' loading conditions with free seepage forces, it is predicted that a much better

simulation of field conditions in zoned dams can be achieved. The equipment is referred to in subsequent text as the HF-cell (Figure 2).

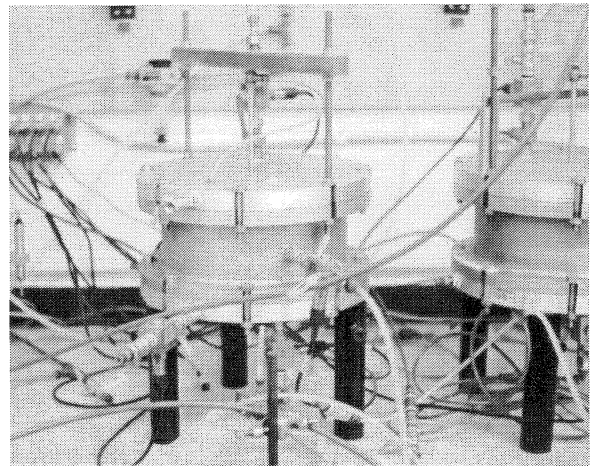


Figure 2. Hydraulic consolidation cell (Rowe cell) for nominal sample diameter of 250 mm. The HF-Test Apparatus

3.2 Laboratory versus Field Stress Conditions

In the HF-cell it was assumed that $\sigma_1 = \sigma_t$ and $\sigma_3 = \sigma_\theta + \sigma_t$, where σ_t is the tensile strength of the soil. The pore water pressure u in both situations (field and laboratory) is a function of the seepage force generated by a radial flow of water pushing its way through the core (or specimen). It is induced by the seepage water pressure from the reservoir which is assumed to be equivalent to the seepage water pressure gradient given by a pressure difference $\Delta P = P_i - P_o$. This pressure gradient creates forces acting radially in the specimen in an outwards direction, since $P_i > P_o$.

The overburden pressure $\sigma_1 = \gamma D$, in the field (a major principal stress) is represented by the radial hoop stress σ_r , which is a major principal stress in the HF-test. The reason for the radial stress to be considered as a major principal stress is that the diaphragm pressure, σ_v , is maintained constant and less than the internal water pressure P_i . The external water pressure P_o is kept constant and also less than diaphragm pressure (i.e. $P_o \approx 0.90 \sigma_v$). This boundary stresses allows the HF-test to be modelled assuming a plane-strain condition, with no strain ($\epsilon_v = 0$) on the axial dimension of the hollow cylindrical specimen.

In the HF-test, the specimen is not enveloped by a rubber membrane as reported in previous studies. This constitutes a special feature of the present HF-cell test. The applied water pressures P_i and P_o interact mutually on the development of the state of

stress within the specimen, which is assumed to be close to the field conditions. The absence of this rubber membrane has been recognised as a critical and more valid approach for any study of the hydraulic fracturing mechanism [Bjerrum and Andersen, 1970]. The cell was adapted to apply three independently named pressures: diaphragm pressure σ_v , external water pressure P_0 , and internal water pressure P_i . The pore water pressure u , was measured from the bottom of the cell (Medeiros, 1994).

4. THE HYDRAULIC FRACTURING PRESSURE

The hydraulic fracturing pressure P_{if} , is generally presented as linearly dependent on the minor principal stress σ_3 (or σ_H , the minimum horizontal stress). The empirical relationship can be expressed as follows:

$$P_{if} = m \cdot \sigma_H + n \quad (2)$$

where,

m and n are constants.

The above equation may be interpreted as a situation where, if all other factors are isolated, the hydraulic fracturing pressure is a linear function of the minor principal stress (Morgenstern and Vaughan, 1963; Vaughan, 1971; Jaworski, 1979; Mori and Tamura, 1987; Panah and Yanagisawa, 1989; Lo and Kaniaru, 1990).

The minimum horizontal stress, i.e. σ_{Hmin} may be the initial horizontal stress or the confining pressure, or the closing pressure according to Bjerrum and Andersen (1972) and to Bozozuk (1974).

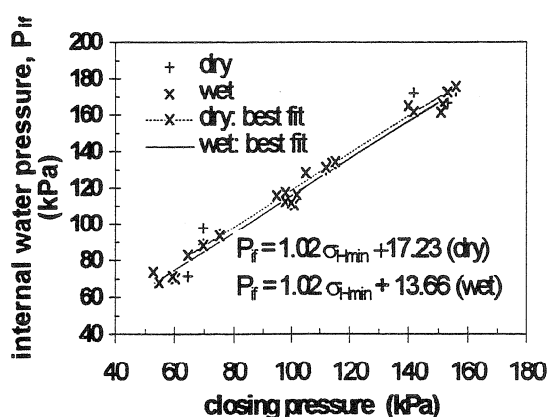


Figure 3. Plot of hydraulic fracturing pressure, P_{if} versus closing pressure, σ_{Hmin}

4.1 Stress Paths: p-q and p'-q Diagrams

The assumption that the closing pressure is equal to the minor principal stress σ_3 was questioned by Penman, who found values of σ_3 , to be less than the closing pressure or σ_{Hmin} [Penman and Charles, 1981]. In this research programme, the σ_{Hmin} values were obtained using the method recommended by Bozozuk (1974).

A linear relationship was established between these minimum horizontal stress values and the corresponding measured hydraulic fracturing using the empirical formulae outlined in the literature (Figure 3).

The evolving stress conditions during the hydraulic fracture test are shown in Figure 4. The values for σ_r and σ_θ were calculated using equations given by elastic theory, substituting P_i and P_0 values and assuming $a = 20$ mm and $b = 75$ mm. The p-q stress points were calculated by using the following expressions:

$$p = \frac{1}{2}(\sigma_r + \sigma_\theta) \quad (3)$$

and

$$q = \frac{1}{2}(\sigma_r - \sigma_\theta) \quad (4)$$

where,

$$\begin{aligned} \sigma_1 = \sigma_r & \text{ is the major principal stress,} \\ \sigma_3 = \sigma_\theta & \text{ is the minor principal stress.} \end{aligned}$$

The internal water pressure, P_i was increased until fracture occurred at a pressure P_{if} , and it was assumed that the sample fractured as a result of tensile stress (Jaworski, 1979; Seco e Pinto, 1983).

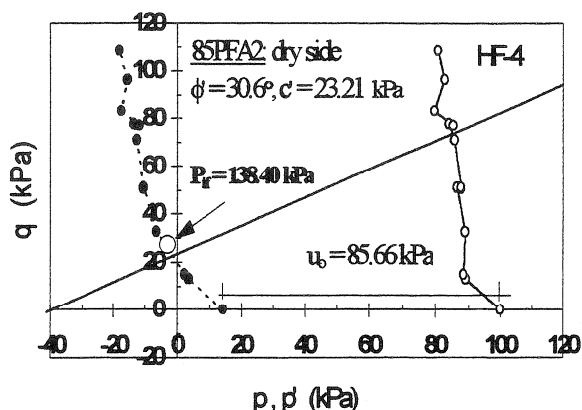


Figure 4. Stress-path diagram, obtained for HF-4.

According to Vaughan (1971) an increase in pore water pressure u , due to seepage, would lead to a decrease in effective stress. This change in effective stress would result in some stress redistribution. As a consequence, the minor principal stress σ_3 , may become less than the tensile strength σ_t , of the soil and the sample may fail by tensile stress.

By assuming a linear Mohr-Coulomb criterion with some modification in its general form, as suggested by Lo and Kaniaru (1990), and by making the major principal stress σ_1 , equal to the radial stress, σ_r , and the minor principal stress σ_3 equal to the tangential stress σ_θ , the revised equation will assume the form:

$$(\sigma_r - \sigma_\theta) - (\sigma_r - \sigma_\theta) \sin \phi = 2c \cos \phi \quad (5)$$

The values of the radial and tangential stresses were obtained using the elastic solution presented in Timoshenko and Goodier (1965). They are a function of the geometry of the annular specimen and the magnitudes of the applied external and internal pressures, P_i and P_o respectively.

It can be seen from these assumptions that it is possible to plot the stress path which represents the stress changes during the hydraulic fracturing test. It follows that as the internal water pressure, P_i is increased while the external water pressure, P_o is kept constant, tensile tangential stress is induced and the hydraulic fracturing takes place by tension failure at a value dependent upon the choice of the failure envelope [Lo and Kaniaru, 1990]. A failure envelope of effective stress from the triaxial CD-test performed on specimens 85PFA2 at OMC-2% was chosen as an example (Figure 4). A series of HF-Tests were performed at OMC+2%. It is important to remember that post-failure hydraulic fracturing tests on Teton Dam (USA) core material were performed on specimens compacted at OMC+3% and Llyn Brianne Scammonden Dam (UK) at OMC+1%.

At failure, the tensile fracture is assumed to develop perpendicular to the minimum principal stress, which in this type of test was assumed to be the minimum tangential stress. Corresponding boundary stresses and possible stress-paths during hydraulic fracturing tests which result from vertical fractures, have been presented by Ljunggren and Amadei (1989) and are further discussed in Hefny and Lo (1992). A stress inequalities for vertical fracture (for stress path type II) is:

$$\sigma_r > \sigma_z > \sigma_\theta \quad (6)$$

and

$$\sigma_\theta < 0 \quad (7)$$

The HF-test boundary stress conditions follow the inequalities of stress path type II. In all tests in this investigation a vertical fracture was observed (Figure 5).

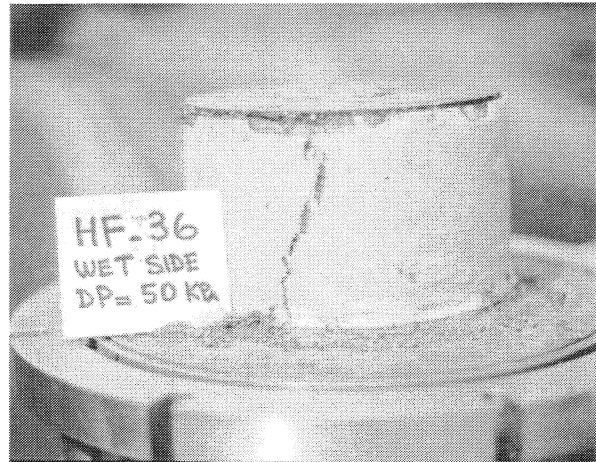


Figure 5. Crack patterns of fractured specimen test HF-36. Pressure increment rate of 10 kPa/min, specimen compacted at OMC+2%. DP is the Rowe Cell diaphragm pressure.

5. CONCLUSIONS AND RECOMENDATIONS

The stress-path p - q and p' - q diagrams obtained (Figure 4) follow the plotting procedure suggested by Lo and Kaniaru (1990). It can be seen from Figure 4 that the measured hydraulic fracturing pressure P_{if} clearly touches the effective stress failure envelope at a point which, by a simple calculation using equations (6) and (7), gives $\sigma_3 = \sigma_\theta \cong -19.0$ kPa (a tensile stress). This value lies close to the range for tensile strength obtained using mix 85PFA2 at OMC-2%, i.e. $\sigma_t = 21.73 \pm 0.91$ kPa. It can, therefore, be concluded that the HF-test results supported the hypothesis that a vertical fracture occurred by a tension failure mechanism induced by hydraulic fracturing. The stress-paths obtained for those tests (in terms of total and effective stress), as presented in Figure 4, also agree with the possible cracking mechanism presented by Vaughan (1971) and the mode of failure (vertical fracture) suggested by Ljunggren and Amadei (1989).

The HF-test results also provide strong evidence for the validity of the assumption that an hydraulic fracturing occurs if the minor principal effective stress σ'_3 (or closing pressure, σ_{Hmin}), becomes negative or tensile with a magnitude exceeding the tensile strength of the soil σ_t . (i.e. $\sigma'_3 + \sigma_t \leq 0$), (Medeiros, 1994, 1995a and 1995b).

The hydraulic fracturing pressure P_{if} overestimates the 'closing pressure' σ_{Hmin} by 15.21%. The measured 'closing pressure' in the HF-test, was also derived from the crack 'closing pressure' concept which should be less than the cracking 'opening pressure', as a result of the tensile strength of the soil. The points discussed above provide evidence for this.

The hydraulic fracturing is a tension failure mechanism. It was confirmed by plotted stress-path diagrams in terms of 'hoop stresses', as suggested by Lo and Kaniaru (1990) and Hefny and Lo (1993). The results obtained in the HF-tests also support the hydraulic fracturing mechanism advanced by Morgenstern and Vaughan (1963), using the Mohr-Coulomb failure criterion. The HF-test results indicates that the Mohr-Coulomb failure criterion should be applied to investigate the hydraulic fracturing mechanism.

6. ACKNOWLEDGEMENTS

The author was supported by the Brazilian government, through the combined sponsorship of the Universidade Estadual de Feira de Santana, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), and Newcastle University, United Kingdom.

7. REFERENCES

- Bjerrum, L. and Andersen, K.H. (1972)- In situ measurements of lateral pressures in clay. Proceedings of 5th European Conference on Soil Mechanics and Foundation Engineering, Madrid, Vol.1, pp. 11-20.
- Bozozuk, M. (1974)- Minor principal stress measurements in marine clay with hydraulic fracture tests. Proc. of Speciality Conf. Subsurface Exploration for Underground Excavation and Heavy Construction, pp. 333-349.
- Carneiro, F.L.L. and Barcellos, A. (1953) - Tensile strength of concrete. Bulletin No. 13, The International Union of Testing and Research Laboratory for Material and Construction, pp. 99-125, Paris, France.
- Hassani, A.W., Singh, B., Saini, S.S. and Goel, M.C. (1985)- Laboratory simulation of hydraulic fracturing. Proceedings of 11th Int. Conf. on Soil Mechanics and Foundation Eng., San Francisco, California, Vol.2, pp. 1081-1084.
- Hefny, A. and Lo, K.Y. (1992)- The interpretation of horizontal and mixed-mode fractures in hydraulic fracturing tests in rock. Canadian Geotechnical Journal, Vol. 29, pp.902-917.
- Jaworski, G.W. (1979)- An experimental study of hydraulic fracturing. PhD Thesis, University of California, Berkeley, 268 pp.
- Lo, K.Y., Kaniaru, K., (1990). Hydraulic fracture in earth and rockfill dams. Can. Geotech. J., no. 27, pp. 496-506.
- Ljunggren, C. and Amadei, B., (1989) - Estimation of virgin rock stress from horizontal hydrofractures. Int. Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 26, pp. 69-78.
- Medeiros, C.H. de A. C. (1994)- A Laboratory Simulation of the Hydraulic Fracturing Mechanism in Embankment Dams. PhD Thesis, University of Newcastle upon Tyne, England.
- Medeiros, C.H. de A. C. and Moffat, A.I.B., (1995)- Hydraulic fracturing using the Rowe consolidation cell. Proc. 11th Eur. Conf. Soil Mech. Fndn. Eng., Copenhagen, 28 May -1 June. Danish Geotechnical Society, Bulletin 11, Vol. 3, pp. 3.185-3.190.
- Medeiros, C.H. de A. C. and Moffat, A.I.B., (1995)- A hydraulic fracturing test based on radial seepage in the Rowe consolidation cell. Proceedings Int. Conf. on Advances in Site Investigation Practice. Institution of Civil Engineers, London, 30-31 March.
- Morgenstern, N.R., and Vaughan, P.R. (1963)- Some observations on allowable grouting pressures. Proceedings of Conference on Grouts and Drilling Muds. Institution of Civil Engineers, London, pp. 36-42.
- Mori, A. and Tamura, M. (1987)- Hydrofracturing pressure of cohesive soils. Soils and Foundations, Vol. 27, No. 1, Mar., Japanese Society of Soil Mechanics and Foundation engineering pp. 14-22.
- Panah, A.K. and Yanagisawa, E. (1989)- Laboratory studies on hydraulic fracture criteria in soil. Soils and Foundations, Vol. 29, Japanese Society of Soil Mechanics and Foundation engineering, No. 4, pp. 14-22.
- Penman, A.D.M., Charles, J.A. (1981)- Assessing the risk of hydraulic fracture in dam cores. Proceedings of 10th Int. Conf. on Soil Mech. and Found. Eng., Stockholm, Vol. 1, pp. 457-462.
- Rowe, P.W., and Barden, L. (1966)- A new consolidation cell. Geotechnique, 16, 2, pp. 162-169.
- Seco e Pinto, P.S., (1983)- Hydraulic fracturing in zoned earth and rockfill dams. Thesis presented for the degree of Researcher of LNEC, Lisbon, Portugal.
- Timoshenko, S. and Godier, J.N. (1965)- Theory of elasticity. McGraw-Hill, New York, 506 pp.
- Vaughan, P.R., (1971)- The use of hydraulic fracturing tests to detect crack formation in embankment dam cores, Interim Report, Department of Civil Engineering, Imperial College, London.