Laboratory simulation of hydraulic fracturing

Simulation en laboratoire de fracturation hydraulique

A. WAHED HASSANI, Research Scholar, University of Roorkee, Roorkee, India
BHARAT SINGH, Vice-Chancellor, University of Roorkee, Roorkee, India
S. S. SAINI, Professor, Civil Engineering Dept., University of Roorkee, Roorkee, India
M. C. GOEL, Professor, WRDTC, University of Roorkee, Roorkee, India

SYNOPSIS To find out the pressure causing initiation of hydraulic fracturing in soil mass, a laboratory experimental set up simulating the bore hole condition is presented. Further, based on test results, the effect of various parameters on hydraulic fracturing such as degree of saturation, confining pressure, rate of pressure application, etc. is discussed.

INTRODUCTION

The induced cracking in the soil mass due to excess hydraulic pressure is called hydraulic fracturing which occurs when the applied hydraulic pressure exceeds the minimum stress in the fracture region. This phenomenon is important for the safety of earth dams against cracks and for loss of drilling fluid through bore holes in earthen structures.

In order to study the phenomenon of hydraulic fracturing in cylindrical soils, a laboratory experimental technique has been developed. The technique is based on the measurement of induced hydraulic fracturing pressure inside a hollow cylindrical soil specimen subjected to uniform confining pressure.

EXPERIMENTAL SET UP

Figure 1 shows a diagramatic layout of the experimental setup, composed of five units. Unit I consists of soil specimen enclosed in a rubber membrane and placed in the triaxial cell. To measure the volume changes a single burette volume change apparatus (Unit II) is used. The self compensating mercury control system (Unit III) is used for application of constant confining pressures. Bishop's pore pressure apparatus consisting of hand operated screw type hydraulic pump, pressure gauge, mercury manometer but without mercury null indicator as shown in Unit IV, is used for application of hydraulic fracturing pressure through the hollow of the cylindrical specimen. Unit V is complete Bishop's pore pressure measuring unit including null indicator to measure pore pressures.

Soil Properties

Soil used for experimental investigation was classified as CL soil based on unified soil classification system. The composition of soil was, sand 40%, silt 41% and clay 19%. The liquid and plastic limits were 32.5% and 22% respectively. Dry density was 1770 kg/m^3 at 16.5% OMC. Average tensile strength of soil was 2.45 N/cm^2 and 0.98 N/cm^2 at OMC and saturated condition respectively.

Specimen Preparation

The specimen was prepared in Proctor's mould with some modifications. To obtain a central hollow space, a 1.27 cm dia. rod was placed centrally inside the Proctor's compaction mould over a matching hole in 0.4 cm thick plate placed in the mould over base plate. Due to placement of this rod, conventional method of imparting blows by hammer, could not compact soil uniformly. Hence a rigid steel frame having three plates was made and soil compacted in three layers by placing this frame over the soil and imparting blows over the top plate(Fig.2). The number of blows required per layer increased to 60 in order to achieve the standard Proctor's density.

Experimental Techniques and Testing Conditions

Two aluminium collars 10.16 cm in diameter and 3.81 cm in thickness were glued to the top and bottom of the soil specimen by an adhesive. The upper collar had a connection for airvent and bottom collar a connection firstly for saturating the sample and subsequently for applying hydraulic fracturing pressure. An injection needle of 1.0 mm diameter with holes on the periphery was fixed to the upper collar so as to be inserted in to the middle thickness of the soil cylinder up to mid height, to detect whether the sample was saturated and to measure pore pressure.

To prevent direct exposure of the soil to water, filter paper was placed at inner surface of the soil cylinder. The soil specimen so prepared represents a bore hole confined at both ends.

The specimen enclosed in rubber membrane was subjected to a small head of 20 cm. of water from inside the hollow of cylinder for a minimum of 15 days for saturation. On completion of saturation the specimen was placed in triaxial cell and subjected to confining pressure through unit III. The internal pressure was applied through hand pump of unit IV and was increased linearly to induce hydraulic fracturing.

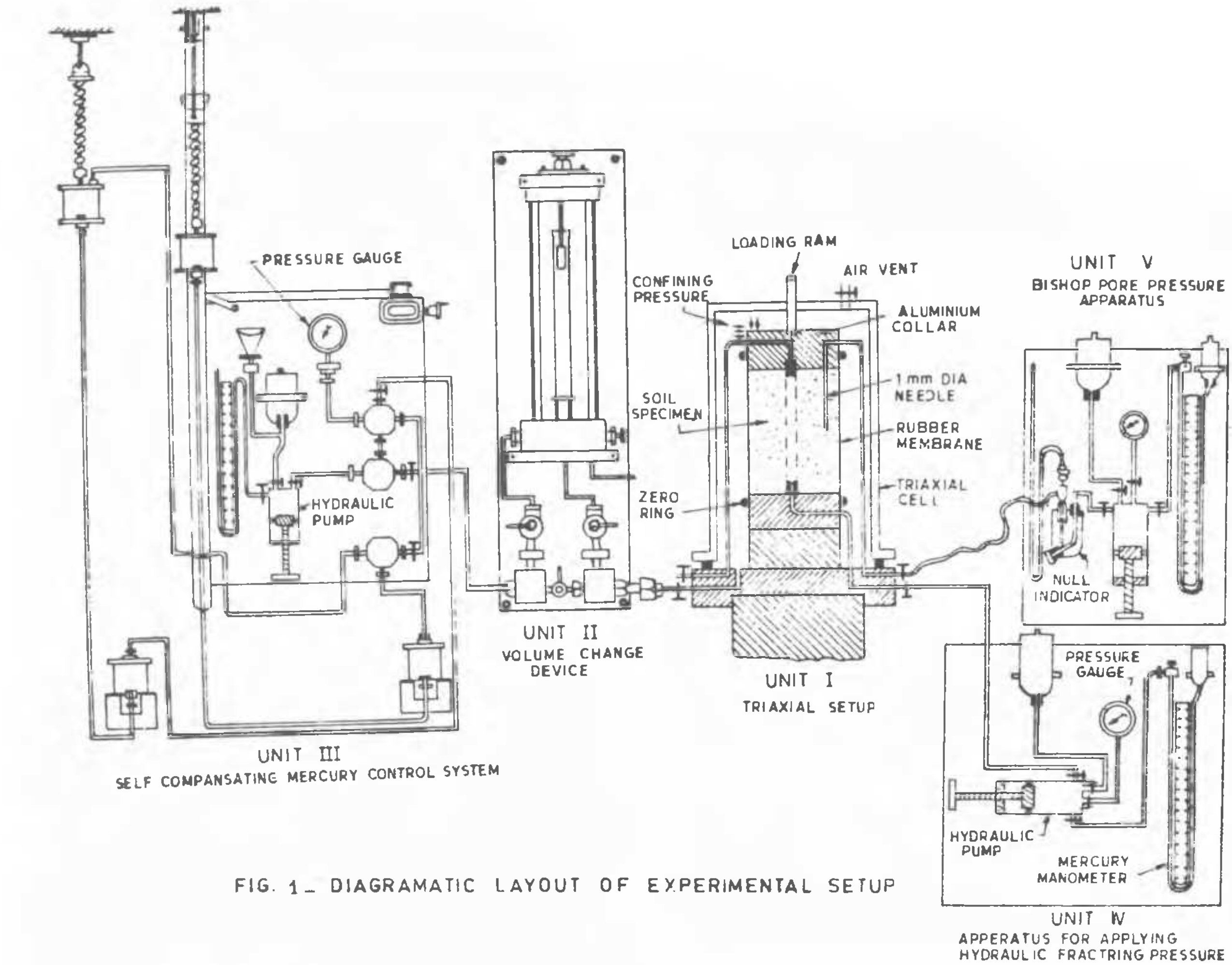

FIG. 1 – DIAGRAMATIC LAYOUT OF EXPERIMENTAL SETUP

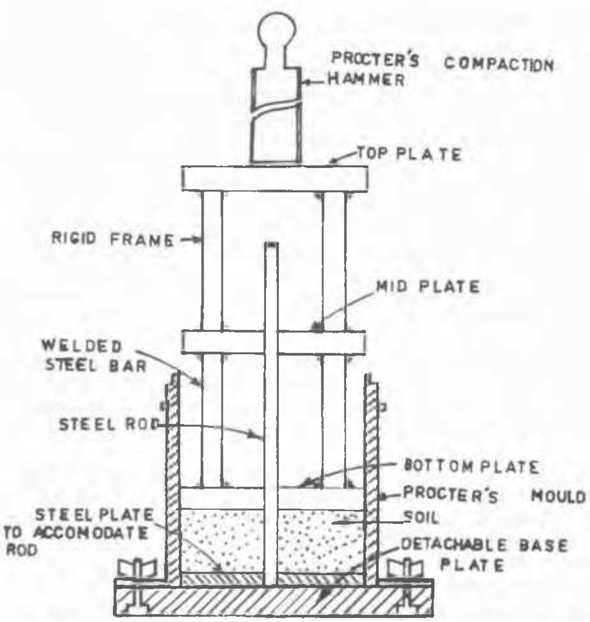

FIG.2 SPECIMEN COMPACTION ARRANGEMENT

Hydraulic fracturing in the soil sample was detected by sudden drop of pressure read either by manometer or pressure gauge. The drop in pressure indicates the formation of cracks. After the completion of test, both external and internal pressures were slowly decreased to zero and the specimen was carefully examined for the orientation of cracks.

Experiments were conducted at various confining pressures ranging from zero upto 21.58 N/cm^2. Three to five specimens were tested at each range of confining pressure in order to have repeatable values. Samples were tested for (a) saturated condition and (b) partially saturated condition. In addition, the effect of initial degree of saturation was also studied by compacting the specimens at OMC, and $\pm$ 1% OMC. The internal pressure into the hollow of cylindrical specimen causing hydraulic fracturing was applied at three different rates viz.(i) instantaneous(ii) short duration and (iii) long duration.

Under instantaneous application of pressure the water pressure was increased through the hand pump in a very short period of half to one

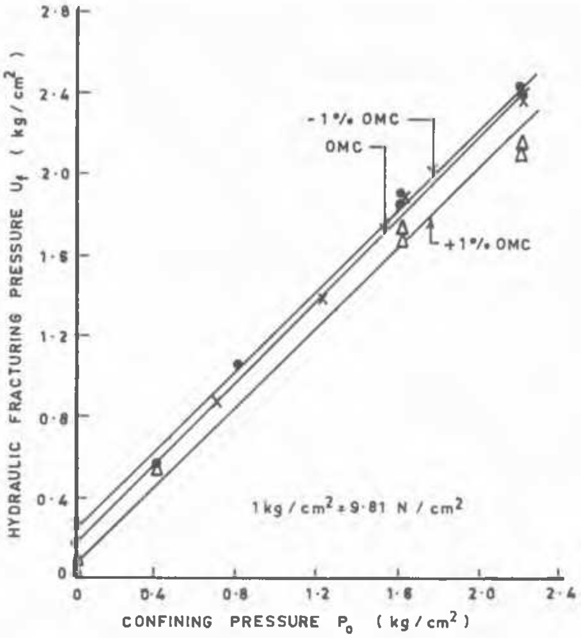

FIG.3 - EFFECT OF INITIAL MOISTURE CONTENT ON SATURATED SAMPLES

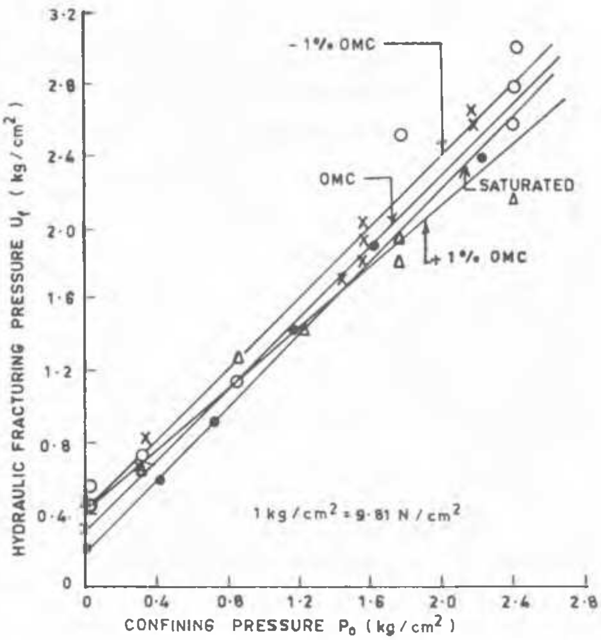

FIG.4 - COMPARISON OF PARTIALLY SATURATED AND SATURATED SAMPLES

minute. Short duration tests were carried out causing fracture by increasing water pressure in a period of round about 15 minutes. In long duration tests, the internal pressure was increased in incremental steps over a total period varying from 3 hours to 24 hours depending upon the range of confining pressure.

RESULTS AND DISCUSSIONS

The experimental results of short duration tests conducted at various confining pressures on saturated specimens compacted at OMC, and ± 1% OMC are presented in Fig.3 as plots of hydraulic fracturing pressure U_f, against total confining pressure P_o. The plots show that U_f is a linear function of P_o. From the figure it is seen that the slope of line giving relationship in between U_f and P_o is, 1.01, 1.00 and 0.99 for initial moisture content at -1% OMC, OMC and + 1% OMC, whereas corresponding vertical intercepts are 2.45, 1.77 and 0.98 N/cm^2 against tensile strength of 0.98 N/cm^2. This shows that (i) hydraulic fracture pressure is slightly more than the confining pressure in all the three cases, (ii) slope of line is independent of initial degree of saturation and is close to unity, and (iii) vertical intercept decreases with increasing initial moisture content and in the worst case, it is equal to the tensile strength of the soil, otherwise it is more than that.

The test results of hydraulic fracturing pressure on partially saturated specimens are presented in Fig.4. From this figure it is again inferred that the relationship between U_f and P_o is a linear one. Further it is seen that as compactive moisture content increases, the hydraulic fracturing pressure required for initiation of cracks decreases. The slope of line connecting U_f and P_o is 1.01 and 0.99 for compaction at -1% OMC and at OMC which is again close to unity as was in the case of saturated samples. However, at +1% OMC, the slope of line is 0.91 which is slightly on the lower side. Also the line fit is not so good. This may be because of the limitations and complex nature of soil phenomenon. The vertical intercepts are 4.02, 3.83 and 3.34 N/cm^2 for -1% OMC, OMC and +1% OMC against measured tensile strength of 2.45 N/cm^2 for sample prepared at OMC and tested by Brazilian technique. This shows that as the initial compactive moisture increases, vertical intercept decreases but in all cases, the value is more than the tensile strength of the soil at OMC.

For comparison of hydraulic fracturing pressures of partially saturated soils with saturated soils, the test results of specimens compacted at OMC and then saturated are also reproduced on the same figure. From this it could be seen that hydraulic fracturing pressures for partially saturated soils, compacted at -1% OMC and at OMC, are always higher than those for the saturated case. The slope of the line in all the cases, is the same, but the difference is in the vertical intercept. Higher value of vertical intercept for partially saturated soil can be attributed to the presence of negative capillary pressure. In case of compaction at +1% OMC, hydraulic fracturing pressure is more as compared to that for saturated case in the confining pressure range of 0-14.72 N/cm^2, however, beyond this range, the trend is reversed. This is attributed to complex soil phenomenon and experimental limitations.

The results of tests performed at different rates of pressure application, are plotted in Fig.5. It is seen that as the duration of test

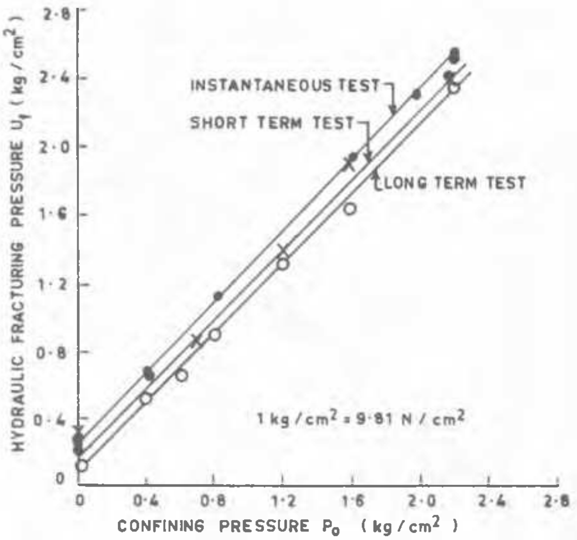

FIG.5-EFFECT OF RATE OF APPLICATION OF PRESSURE

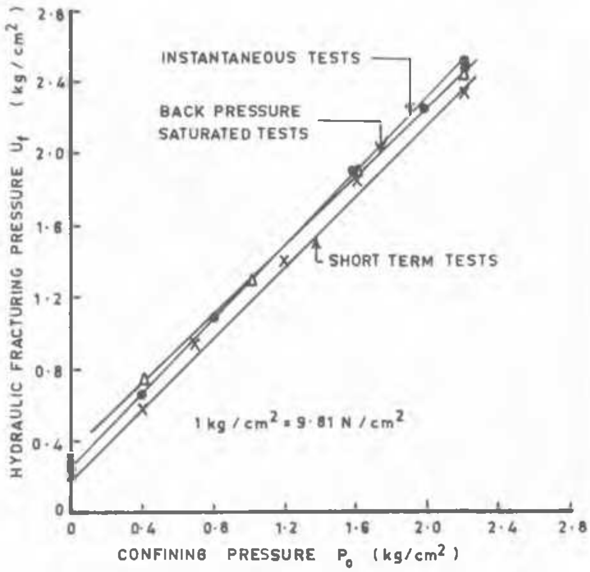

FIG.6 COMPARISON OF CONVENTIONALLY SATURATED AND BACK PRESSURE SATURATED SAMPLES

increases, hydraulic fracturing pressure decreases, provided, other conditions remain unchanged. As expected, the variation is in vertical intercept and the variation in slope is negligible. The vertical intercept increases from 0.98 N/cm^2 for long duration test to 2.55 N/cm^2 for instantaneous test.

IMPROVEMENT IN TESTING TECHNIQUE

The results presented herein are based on conventional saturation technique described earliear. However, subsequently, it was felt that saturating the specimen by back pressure technique would be better. Hence in subsequent experimentation, the saturation was done by applying back pressure into the hollow of the cylindrical specimen through unit IV. Simultaneously the pore pressure measurements were also taken through the needle embedded in the specimen by unit V. The results for back pressure saturated test specimens compacted at OMC are presented in Fig.6. These tests were conducted by applying internal pressure causing fracture for a period upto three minutes depending upon the range of confining pressure. For comparison, the results of conventionally saturated tests, are also plotted in the same figure for instantaneous and short duration tests. From the figure, it is seen that the results of back pressure saturated specimens are in close agreement with those of the previous instantaneous test. The slope of line for back pressure saturation is 0.97 against 1.03 for instantaneous conventionally saturated test specimen. The U_f value for back pressure saturated case is slightly higher than that of instantaneous case upto 13.73 N/cm^2 confining pressure and thereafter, the trend reverses. The difference is about 10% and within the range of experimental variation. As expected the U_f values for back pressure saturated samples, stressed to failure within three minutes, are higher than those for short duration tests conducted in about 15 minutes time on conventionally saturated samples. Evidently there is no significant difference in test results of samples saturated under low heads or by back pressure.

CONCLUSIONS

The following are the main results of the investigations presented in this paper :

(1) An experimental technique has been developed to find out the hydraulic fracturing pressure causing crack initiation in case of hollow cylinders using triaxial machine.

(2) Hydraulic fracturing pressure U_f, and alround confining pressure P_0, is linearly related as also found by others (Decker and Clemence 1981, Jaworski, et.al.,1981).

(3) Hydraulic fracturing pressure for partially saturated soils is greater than that for saturated soils.

(4) In case of saturated samples, hydraulic fracturing pressure reduces with increasing initial degree of saturation.

(5) With increase in time of application of pressure, the value of hydraulic fracture pressure decreases.

REFERENCES

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Jaworski, G.W., Duncan, J.M. and Seed, H.B., (1981), ' Laboratory Study of Hydraulic Fracturing', ASCE, GT6.