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Stress-path on the hydraulic fracturing test of the clay core of rock fill dams in the laboratory

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Abstract

Hydraulic fracturing on the rock fill dam is described as a phenomenon of cracks on the upstream face of clay core of rock fill dams due to the tension failure. This situation may arise if the total stress in the core is reduced by arching effect and increasing pore water pressure in the core during impounding. Hydraulic fracturing on the rock fill dams can be modelled in the laboratory. The reduction of the total overburden stress due to arching effect and hydraulic pressure from the water in the reservoir can be modeled in the laboratory by applying the initial stress states and water pressure to the specimens. The soil specimens were compacted in a hollow cylinder. The dimension of the soil specimen was 100 mm in diameter and 120 mm high, while the inner diameter of the borehole was 18 mm. The paper present an initial hydraulic fracturing test at 5 (five) different initial stress states in order to investigate the tension fracture mechanism. The stress paths during hydraulic fracturing tests indicated the tension fracture to the soil specimens occurs on the soil specimens which the initial stresses fall in the envelope of \(\frac{1}{2}(\sigma_y - \sigma_x) < c\).

Keywords: Hydraulic fracturing; Stress-path; Clay Core; Rock Fill Dams

1. Introduction

Soils have widely used as embankment materials for earth fill dams and clay core materials in rock fill dam engineering. As a clay core material, soil should be impermeable, for it has sufficient shear strength and tensile strength to resist against hydraulic fracturing. Soils as materials for core of rock fill dams may have wide range of fine contents, Fell et al [1]. Soils also may consist of different clay minerals that affected to their engineering properties

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and performance. In the fields the condition of compaction also may varied from dry to wet. The variation of soils may produce different resistance against hydraulic fracturing. Hydraulic fracturing becomes one of the major problems in rock fill dams, since it plays significant role in the initiation and extension cracks in the clay core, which may result in leakage and internal erosion. The mechanism of hydraulic fracture in soils has been studied in the laboratory by some researchers Nobari et al. [2], Jaworski et al. [3], Widjaja et al. [4], Hassani et al. [5], and Panah and Yanagisawa, [6]. Recent investigation by Ohne et al [7] on the possibility of hydraulic fracturing in embankment dam during earthquake using seepage fracture tests were carried out in various condition of pore water pressure, overburden confining pressure and dynamic shear stress induced by earthquake. These studies have shown that water pressure can induce hydraulic fracturing in soils, however, important factors influencing hydraulic fracture in the clay core of embankment dams such as water contents, degree of saturation, degree of compaction, fine contents, clay mineral, as well as initial stress state receive little consideration.

In this study the hydraulic fracturing apparatus was made to model the fracture on the upstream of the clay core of the rock fill dams. The reduction of the total overburden stress due to arching effect and hydraulic pressure from the water in the reservoir can be modelled in the laboratory by applying the initial stress states and water pressure to the specimens. Mode of failure of the clay core of a rock fill dam due to hydraulic fracturing has been justified as a tension failure. The soil samples for hydraulic fracturing test in the laboratory were taken from the borrow pits of the 6 major rock fill dams in Indonesia; they are Batubulan, Batutegi, Pelaparado, Kedungombo, Sermo and Wonorejo dams. The soil samples were then modeled into six (6) different fine contents, there are the fraction passing sieve no. 200 at 30%, 40%, 50%, 60%, 70% and 80%, in order to investigate the effects of fine contents to the hydraulic fracturing. The variation of moisture contents during the compaction were also carried out, the soil samples were compacted into three (3) different moisture contents, they were (w_{opt}-3%), w_{opt}, and (w_{opt}+3%). The number of the test variations will be 324 in total. These variations were carried out in order to investigate the effects of the moisture contents, degree of compaction, fine contents of the soils as well as stress states against hydraulic fracturing.

In the preliminary hydraulic fracturing tests, Djarwadi et al. [8] were carried out on five (5) variations of initial stress states which were applied to the soil specimens in order to study the effect of stress states on the upstream face of clay core of a rock fill dam to the hydraulic fracturing. The results indicated that the tension failure was only found on the soil specimen if the initial stress state falls in the envelope of \( \frac{1}{2}(\sigma_y - \sigma_x) < c \), where the \( \sigma_y \) and \( \sigma_x \) are the initial vertical and horizontal stresses which are applied to the soil specimens, which reflects the vertical and horizontal stresses on the upstream face of clay core before impounding took place, and \( c \) is the cohesion of the soil specimen. Table 1 shows the initial stress states applied to the soil specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( \sigma_x ) (kPa)</th>
<th>( \sigma_y ) (kPa)</th>
<th>( \frac{1}{2}(\sigma_y - \sigma_x) ) kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100</td>
<td>160</td>
<td>30</td>
</tr>
<tr>
<td>B</td>
<td>140</td>
<td>240</td>
<td>50</td>
</tr>
<tr>
<td>C</td>
<td>180</td>
<td>320</td>
<td>70</td>
</tr>
<tr>
<td>D</td>
<td>200</td>
<td>380</td>
<td>90</td>
</tr>
<tr>
<td>E</td>
<td>240</td>
<td>460</td>
<td>110</td>
</tr>
</tbody>
</table>

2. Properties of the soil specimens

Hydraulic fracturing tests will be carried out on 324 variation of samples from the core materials of 6 dams in Indonesia, the preliminary hydraulic fracturing tests were performed on Batubulan dam clay core material. The aims of the preliminary test were to investigate the condition where the tensile fracture to occur and the stress-path during the tests. The soil sample from Batubulan was well graded with 31.14% fine content. The soil was classified as clay with low plasticity (CL) based on the USCS classification system. The soil specimens were compacted comply to ASTM D 698-00 standard. The maximum dry density and optimum moisture content obtained from compaction tests were 15.32 kN/m³ and 20% respectively, while the internal angle of friction and cohesion obtained from triaxial UU test were 18.15° and 78.20 kPa.

The specimens were compacted hollow cylinder soil. The specimens were compacted inside a Proctor mould measuring 100 mm in diameter and 120 mm high. The inner diameter of the borehole was 18 mm, based on the
borehole fracturing research results by Widjaja et al. [4]. Fig.1 shows the typical soil specimen used in the hydraulic fracturing tests.

![Image](image1.png)

Fig 1. Sketch and actual soil specimen.

3. Hydraulic fracturing test apparatus

The development of hydraulic fracturing test apparatus of clay core in the laboratory has a limitation that not all the conditions in the dams can be modeled in the laboratory. The reduction of the total overburden stress due to arching effect can not be exactly modeled in the laboratory, since the factors affecting arching effect such as different of stiffness in the embankment materials, the slope of abutments, and the configuration and bottom width of the clay core will varied from site to site of the dams. The reduction of the total stress due to arching will be modeled by applying different initial stress states to the soil specimen prior the tests were started. The development of the hydraulic fracturing test apparatus in laboratory mainly will focus to investigate the tensile fracture of clay core due to the wedging. The test apparatus consists of two parts namely; hydraulic fracturing chamber and pressure chamber. The sketch of the cross section of hydraulic fracturing chamber is shown in Fig 2.

![Image](image2.png)

Fig 2. Sketch of the cross section of hydraulic fracturing chamber.

The hydraulic fracturing chamber consists of compacted hollow cylinder soil specimen which clamped in both end platens. The soil specimen then covered by sand that will function as granular filter. The gradation was modelled using no-erosion filter criteria proposed by Sherard and Dunnigan [9]. The outer side of hydraulic fracturing chamber was then covered by latex membrane. The hole inside the soil specimen was also filled with sand. The degree of compaction of the granular filter was modeled similar to the field relative density of granular filter. Most of dams in
Indonesia adopted the lowest field relative density of the filter at 70%. The hydraulic fracturing chamber equipped with channels in order to apply the hydraulic pressure, water flow measurement and pore water pressure measurement. The hydraulic fracturing chamber then fixed on the bottom platen of the pressure chamber. The pressure chamber has the same function with the triaxial chamber, but the size was larger in order to accommodate the hydraulic fracturing chamber dimensions. The confining stress ($\sigma_3$) was applied by water pressure generated by constant pressure machine, while axial stress ($\sigma_y$) was applied by axial pressure generated by electric motor. The development of apparent effective stress during the test monitored using calibrated proving ring. The hydraulic pressure to the soil specimen was increased gradually to model the increasing of water level in the reservoir. The water flow through the soil specimen was monitored using micro-flow meter and transducer, while the confining pressure which assumed uniform during the test was monitored using pore pressure transducer. Both transducer supplied real time data to the Automatic Data Acquisition Unit (ADU) machine, and then using computer program the data displayed on the screen. When the soil specimen reaches failure, the axial stress, the axial strain, the pore water pressure, the effective stress, hydraulic fracturing pressure as well as the amount of water flowing into the soil specimen can be obtained. The sketch of the hydraulic fracturing test apparatus developed in the Soil Mechanic and Geotechnical Laboratory, Civil and Environmental Engineering Department, Gadjah Mada University shown in Fig 3.

![Sketch of the hydraulic fracturing test in the laboratory.](image)

**4. Stress equilibrium at the soil specimen**

The stress on the soil specimen during the hydraulic fracturing test is assumed constant. The stress equilibrium on the soil specimen at the end of the test for tension failure is shown in Fig. 4. Two (2) stress equilibrium on the specimen after fracturing occurred, there are stress equilibrium on the specimen and surroundings crack on the inner borehole wall. The equilibrium of the stress on the specimen and crack tip after crack occurred is as follow:

$$\sigma_1 = \frac{A^2(\Delta\sigma' + \sigma_3) - a^2 u_f}{(A^2 - a^2)}$$  \hspace{1cm} (1)

$$\sigma_i = \sigma'_i - u_f$$  \hspace{1cm} (2)

where $\sigma'_1$ is the vertical effective stress in the specimen, $\Delta\sigma'$ is the apparent vertical effective stress, $\sigma_3$ is the confining pressure, $u_f$ is the hydraulic fracturing pressure, $A$ is the outer diameter of the specimen, $a$ is the borehole diameter, and $\sigma_i$ is tension stress at failure of the specimen.
5. Tests results

The test results were summarized in Table 2, and the soil specimens condition after tests were shown in Fig 5, while the stress-path during the hydraulic fracturing tests in which indicated the failure stress-path were shown in Fig 6.

Table 2. Preliminary hydraulic fracturing test results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Initial stress states (kPa)</th>
<th>$\Delta \sigma$ (kPa)</th>
<th>$\sigma_1^\prime$ (kPa)</th>
<th>$\sigma_1^\prime$ (kPa)</th>
<th>$\sigma_1^\prime$ (kPa)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>160 100</td>
<td>43</td>
<td>170</td>
<td>142</td>
<td>-28</td>
<td>Fig 5a</td>
</tr>
<tr>
<td>B</td>
<td>240 140</td>
<td>44</td>
<td>205</td>
<td>183</td>
<td>-22</td>
<td>Fig 5b</td>
</tr>
<tr>
<td>C</td>
<td>320 180</td>
<td>53</td>
<td>240</td>
<td>233</td>
<td>-7</td>
<td>Fig 5c</td>
</tr>
<tr>
<td>D</td>
<td>380 200</td>
<td>66</td>
<td>255</td>
<td>266</td>
<td>11</td>
<td>Fig 5d</td>
</tr>
<tr>
<td>E</td>
<td>460 240</td>
<td>54</td>
<td>270</td>
<td>295</td>
<td>25</td>
<td>Fig 5e</td>
</tr>
</tbody>
</table>

Fig 5. Fracture directions of the preliminary hydraulic fracturing test.
Table 2 shows that when the initial stress state applied to the specimens fell within \( \frac{1}{2}(\sigma_1 - \sigma_3) < c \), the stress failure would be negative or the tension failure would occur as shown on the Fig 5a, 5b and 5c, where the failure plane was horizontal as indicated on the Fig 4, while when the initial stress state was within \( \frac{1}{2}(\sigma_1 - \sigma_3) > c \), the stress failure would be positive or the shear failure would occur. This situation conforms to the investigation by Vaughan [9]. He pointed out that under some conditions shear failure might be expected to occur before tension failure, as the pore pressure is increased while the effective stress is reduced.

The failure stress-path for specimen A, B and C in Fig 6 shows that the failure occurred on the tension condition, while for specimen D and E failure occurred before the tension condition was reached.

The test results have also enhanced the understanding of the mechanism of hydraulic fracturing of rock fill dams in the field, where it may occur if the stress state on some point in the upstream face of the core falls within \( \frac{1}{2}(\sigma_1 - \sigma_3) < c \) due to the arching.

6. Conclusion

The preliminary hydraulic fracturing test using 5 different initial stress states in the laboratory to investigate the failure mechanism were presented, and the following conclusion can be made:

a. The tension failure only occurred when the initial stress states applied on the soil specimen before the test were commenced fell within \( \frac{1}{2}(\sigma_1 - \sigma_3) < c \).

b. Considering the test results, hydraulic fracturing of rock fill dams in the field may occurred in case the stress states on some points in the upstream face of the clay core were falls within \( \frac{1}{2}(\sigma_1 - \sigma_3) < c \) due to the arching.
References