Investigation on the resistant of tropical residual soils as clay core of rock fill dams against hydraulic fracturing

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ABSTRACT

Tropical residual soils derived from in-situ weathering and decomposition of parent rocks which has not been transported from its original location, are mostly found in Indonesia. They have been used widely as clay core and homogenous embankment dams in Indonesia from long time ago, usage example as in Cipanunjang dam which was built in 1927. Hydraulic fracturing may occur in the upstream face clay core of the rock fill dam in case the vertical effective stress in the core is reduced to levels that are small enough to allow tension fracture to occur. Pore water pressure in the core will also increase during impounding, and this will further reduce the effective stresses in the core. Wedging due to water pressure may crack the upstream face of the clay core. This phenomenon was known as hydraulic fracturing in the rock fill dams.

This paper present the investigation on the resistant of the tropical residual soils as clay core from 5 major dams in Indonesia against hydraulic fracturing. Soil samples are taken from the borrow pits and the clay minerals composition was obtained by x-ray diffraction test. The soil samples then modeled into six different fine content ($\phi < 0,075\text{mm}$); there are 30%, 40%, 50%, 60%, 70% and 80%. Hydraulic fracturing in the clay core of the rock fill dam can be modeled in the laboratory using hydraulic fracturing test apparatus. The soil specimens are compacted hollow cylinder with outer diameter of 104 mm, the height was 120 mm, while the inner diameter was 18 mm. Hydraulic fracturing tests were carried out in the variation of three (3) initial stress states and also three (3) compaction moisture contents.

The test results indicated that the clay core which have greater halloysite clay mineral may have greater resistant against hydraulic fracturing, while the clay core which compacted at wet sides may have greater resistant against hydraulic fracturing.

Keywords: tropical residual soils, hydraulic fracturing, clay core, rock fill dams

1 INTRODUCTION

Tropical residual soils were described as product of physical and chemical weathering which remain in place directly above and in contact with its parent rock. Due to the weathering processes, the minerals of which rock is composed are converted into clay minerals such as kaolinite, illite and montmorillonite, while in volcanic areas the presence of halloysite and allophane were acknowledge. In Indonesia, the homogenous earthfill and rock fill dams were the most types built due to the geological conditions and availability of the soils as embankment materials. In this case the research of the hydraulic fracturing of the tropical residual soils used as clay core of the rock fill dams became an important issue.

Hydraulic fracturing becomes one of the major problems in earth and rock fill dams, since it plays a significant role in the initiation and extension cracks in

the clay core. Arching in the clay core of a rock fill dam may result in leakage and internal erosion. Loftquist (1951) described vertical pressures in thin impervious cores of the 26 m high Holle dam and 34 m high Harspranget dam as being as low as half of the normal overburden pressures. Crack may develop in this situation in case the hydraulic pressure is higher than the vertical pressure in the upstream face of the clay core, as occurred in the incident in Hyttejuvet dam in Norway when an unexpected leakage occurred during the first filling of the reservoir (Kjaernsli and Torblaa, 1968). Similar incidents for the unusual leakage occurred just before the reservoir became full during the initial filling of Balderhead dam in England (Vaughan et al. 1970). The failure of Stockton and Wister dams in USA were suspected as being due to hydraulic fracturing (Sherard, 1973). An investigation to the leakage that occurred at Viddalsvatn dam in

Norway indicated that hydraulic fracturing might be the cause (Vestad, 1976). The mechanism of hydraulic fracture in soils has been studied in the laboratory by some researchers Nobari et al (1973), Jaworski et al (1976), Widjaja et al (1984), Hassani et al (1985), and Panah & Yanagisawa (1989).

2 SOIL PROPERTIES

The hydraulic fracturing tests were performed on Batubulan, Batutege, Pelaparado Sermo and Wonorejo dams clay core material. The x-ray diffraction tests indicated that the Batutege, Pelaparado, and Sermo clay core materials contain halloysite, alpha quartz and hematite clay minerals, while at Batubulan and Wonorejo clay core materials, montmorillonite and feldspar clay minerals were also found. The clay mineral composition obtained from quantitative examination is shown in Table 1.

Table 1. Clay mineral composition of the soil samples (%)

Clay mineral	Btg	Plp	Srm	Btb	Wnj
Halloysite	51.51	66.93	48.08	42.22	42.18
Alpha Quartz	42.92	25.07	40.50	8.06	19.40
Hematite	5.57	8.00	11.42	3.80	6.85
Montmorillonite				25.70	17.47
Feldspar				20.22	14.10

Notation: Btg = Batutege, Plp = Pelaparado, Srm = Sermo, Btb = Batubulan, Wnj = Wonorejo

In order to have variations in the hydraulic fracturing test, the soil was then modeled in the percentage of fine contents, and compaction moistures. There are 6 (six) variation in fine contents (passing sieve no. 200) at 30%, 40%, 50%, 60%, 70% and 80%. Three (3) compaction moistures were carried out to model the field compaction in the dam construction, there are: dry condition (OMC-3%), OMC and wet condition (OMC+3%). 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 (1984). Fig.1 shows the typical soil specimen used in the hydraulic fracturing tests.

Fig. 1. Soil specimen for hydraulic fracturing test.

3 TEST APPARATUS AND METHODS

The development of hydraulic fracturing test apparatus of the clay core in the laboratory has a limitation where not all conditions in the dams can be modeled in such a way in the laboratory. The reduction of the total overburden stress due to arching effect can be modeled in the laboratory by applying the initial stress states to the specimens. In this study the variation of initial stress states were applied to investigate which condition of stress states will lead to the hydraulic fracturing of the clay core of rock fill dams. Modus of failure of the clay core of a rock fill dam due to hydraulic fracturing has been justified as a tension failure. The preliminary hydraulic fracturing tests (Djarwadi et al. 2009) indicated that the tension failure is only found on the specimen if the initial stress state falls in the envelope of $\frac{1}{2}(\sigma_y - \sigma_x) < c$, where the σ_y and σ_x were the vertical and horizontal stresses on the upstream face of clay core before impounding take place. All the cohesion (c) of the soil specimens obtained from triaxial unconsolidated undrained test indicated that all the cohesion values were greater than 50 kPa. Based on this result, the three (3) variations of initial stress states 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 dams to the hydraulic fracturing. Table 2 show the initial stress states applied to the soil specimens.

Table 2. Initial stress states applied to the soil specimen.

Initial stress states	Horizontal stress (σ_x) (kPa)	Vertical stress (σ_y) (kPa)	$\frac{1}{2}(\sigma_y - \sigma_x)$ (kPa)
A	140	200	30
B	200	280	40
C	260	360	50

The development of the hydraulic fracturing test apparatus in the laboratory will mainly focus on investigating the fracture of the soil specimen due to the wedging of the water pressure, which may result in the reduction of the effective stress due to the increasing pore water pressure in the specimen. The test apparatus consists of two parts namely: a hydraulic fracturing chamber and a pressure chamber. The hydraulic fracturing chamber consists of compacted hollow cylinder soil specimen clamped in both ends. The hole inside and surrounding each soil specimen was then covered by sand which would function as granular filter. The gradation was modeled using no-erosion filter criteria (Sherard and Dunnigan, 1989). The outer side of hydraulic fracturing chamber was then covered by latex membrane.

The hydraulic fracturing chamber was then fixed on the bottom platen of the pressure chamber. The pressure chamber has the same function as the triaxial chamber,

but the size was larger in order to accommodate the hydraulic fracturing chamber dimensions. The confining stress (σ_x) was applied by water pressure generated by constant pressure machine, while axial stress (σ_y) was applied by axial pressure generated by electric motor.

The hydraulic pressure to the soil specimen was increased gradually using load control mechanism. The water flow through the soil specimen was monitored using a micro-flow meter and a transducer, while the confining pressure which was assumed to be uniform during the test was monitored using a pore pressure transducer. Both transducer supplied real time data to the Automatic Data Acquisition Unit (ADU) machine, and then using computer program the data were displayed on the screen. The development of apparent effective stress during the test was monitored using a calibrated proving ring.

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 flow into the soil specimen can be obtained. Fig.2 shows the hydraulic fracturing test apparatus developed in the Soil Mechanics and Geotechnical Laboratory, Civil and Environmental Engineering Department, Gadjah Mada University.

Fig 2. Hydraulic fracturing test apparatus.

3.1 Stress Equilibrium of Soil Specimen

The stress on the soil specimen during the hydraulic fracturing test assumed to be same. The stress equilibrium on the soil specimen at the end of the test for tension failure is shown in Fig. 3.

Two (2) stress equilibrium on the specimen after fracturing occurred, which 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 presented as follows;

$$\sigma'_1 = \frac{A^2(\Delta\sigma' + \sigma_3) - a^2 u_f}{(A^2 - a^2)} \quad (1)$$

$$\sigma_t = \sigma'_1 - u_f \quad (2)$$

where σ'_1 is the vertical effective stress in the specimen, $\Delta\sigma'$ is the apparent vertical effective stress, σ_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 σ_t is stress at failure of the specimen.

Fig 3, The stress equilibrium on the specimen and crack tip after the hydraulic fracturing occurred.

4 TEST RESULTS

Due to the difference in clay mineral contents, the test results was presented in two (2) groups, there are the soil samples from Batutegi, Pelaparado and Sermo dams which contain 3 similar clay minerals, and from Batubulan and Wonorejo which contain 5 similar clay minerals.

The results of hydraulic fracturing test in the relationship of fine contents (%) and tension stress at failure (kPa) are shown in Fig. 4 for soil samples taken from Batutegi, Pelaparado and Sermo dams, and Fig 5 for soil samples taken from Batubulan and Wonorejo dams.

Fig 4 shows that soil samples which have greater halloysite clay mineral content may have greater tensile stress at failures. The soil samples from Pelaparado dam which have 66.93% halloysite clay mineral consistently have greater tensile stress at failure comparing with soil samples from Batutegi dam which have 51.51% halloysite clay mineral and soil samples from Sermo which have 48.08% halloysite clay mineral.

Fig 5 also shows the similar tends, where the soil samples from Batubulan dam which have 42.22% halloysite clay mineral consistently have greater tensile stress at failure comparing with soil samples from Wonorejo dam which have 42.18% halloysite clay mineral.

Fig 4. Relationship between fine content and tension stress at failure from hydraulic fracturing tests for Batutegi, Pelaparado and Sermo dams.

5 CONCLUSIONS

Laboratory tests of hydraulic fracturing to study the effects of clay mineral on the tropical residual soils used as clay core of rock fill dams have been presented. A theoretical expression based on the stress equilibrium to calculate the vertical effective stress (σ_1') and tension stress at failure (σ_t) was developed. The main conclusions from this study are summarized below:

- Tension stress at failure (σ_t) tends to increase when the halloysite clay mineral contents on the soil samples were increased.
- For the same soil samples, the tension stresses at failure (σ_t) were increased when compacted on wet side.

- The tension stress at failure (σ_t) were increased, when the fine contents of the soil samples were increased.

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Fig 5. Relationship between fine content and tension stress at failure from hydraulic fracturing tests for Batubulan, and Wonorejo dams.

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