# Height limitation of rock fill dams with tropical residual clay cores against hydraulic fracturing

## Limitation de la hauteur des barrages a enrochement avec un noyau d'argile residuelle tropicale contre la fracturation hydraulique

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ABSTRACT: Tropical residual soils has been used successfully as clay core in the rock fill dams, while hydraulic fracturing was one of the caused of internal erosion on the clay core of rock fill dams. The ratio of the height (H) against the base width (W) of the clay core will influenced to the possibility of the hydraulic fracturing of the rock fill dams. The thin clay core tends to higher risk of hydraulic fracturing occurred in the rock fill dams. This paper reported the research in the height limitation of the rock fill dams due to the ratio of the height against base width (H/W) of the clay core. Finite element analysis using couple analyses between stress & deformation and seepage was adopted. The final stress of the dam during construction will be used as initial stress during impounding stages. The vertical effective stress in the upstream face of the clay core then comparing to the hydraulic pressure at the high water level in the reservoir to indicate the occurrence of hydraulic fracturing. The clay core materials were taken from 5 large dams in Indonesia, and a variation on 6 fine contents, and 3 base width of upstream filter were made. The results indicated that the smaller ratio of (H/W) of the clay core resulting greater height of the dam can be constructed safely against hydraulic fracturing.

RÉSUMÉ : Les sols residuels tropicaux ont ete utilizes avec success comme noyau argileux dans les barrages de remplissage, tandis que la fracturation hydraulique a ete l'une des causes de l'erosion interne sur le noyau argileux des barrages de remblai. La rapport de hauter (H) par rapport a la largeur de base (W) de l'ame d'argile influencera la possibilite de fracturation hydraulique. Le noyau d'argile mince tend a un risque plus eleve de fracturation hydraulique se produit dans les barrage de remplissage de roche. Nous avons etudie la limite de hauteur du barrage en raison du rapport entre la hauteur et la largeur de la base (H/W) du noyau d'argile. L'analyse par elements finis utilisant l'analyse couplee entre la contrainte et la deformation et l'infiltration a été adoptee. Le contraintes finales sur le barrage pendant la construction seront utilisee comme contraintes initiales lors des etapes de melange. Les contraintes effectives verticales dans la face amont de l'ame d'argile puis comparant a la pression hydraulique a haut niveau d'eau dans le reservoir pour indiquer l'apparition de fracturation hydraulique. Les materiaux de noyau d'argile ont été preleves dans 5 grands barrages en Indonesie, et une variation de 6 contenus fins et une largeur de 3 bases de filtre en amont ont été faites. Les resultats indiquent que le rapport plus faible (H/W) du noyau d'argile resultant d'une plus grande hauteur du barrage peut etre construit de manière sure contre la fracturation hydraulique.

KEYWORDS: Hydraulic fracturing, tropical residual soil, finite element analysis.

## 1 INTRODUCTION

Arching effect on the rock fill dams occur when the total stress on the upstream face of the clay core is less than its overburden pressure, while hydraulic fracturing may occur when effective vertical stress on some places in the upstream face of the clay core are less than hydraulic pressure from the reservoir. The three aspects which may influence the magnitude of the arching effects are; the difference of stiffness between embankment zones, the clay core configuration, and the slope of the abutments. Holle and Harspranget dams in Norwegia were reported that the total stress in only 50% of their overburden pressure (Loftquist 1951). The possibility of hydraulic fracturing on the rock fill dams due to load transfer between embankment zones has been analyzed and reported (Kulhawy and Gurtowski 1976). Abutment with slope of 1V : 0.5H reported that the total stress measured was only 52% of their overburden pressure, while on the abutment slope of 1V : 0.85H, the total stress was only 74% (Zhang and Du 1997). The influence of arching effect to the hydraulic fracturing of rock fill dams were analyzed (Zhu and Wang 2004), and found that the increasing of the stiffness or Poisson's ratio and widening the base width of the clay core will reduce the arching effect. Widening of base width of the upstream filter may reduce the arching effect and reduce the risk of hydraulic fracturing on the rock fill dams (Djarwadi et al 2011). The embankment and reservoir impounding rates did not affect to the occurring of hydraulic fracturing (Lo and Kaniaru 1990). Dams with longer construction period allows the greater consolidation comparing to the shorter period, and slower impounding rate allows the wetting and development of the flow-net compare to the faster impounding rates which did not affect to the occurring the hydraulic fracturing. This situation leads to the conclusion that the caused of hydraulic fracturing in the rock fill dams mainly due to the arching effect.

## 2 MATERIAL AND MODELING THE DAM

The soil using for this study were were clay core materials taken from borrow pit of 5 large dams in Indonesia, there are; Batubulan, Batutegi, Pelaparado, Sermo and Wonorejo dams. The soil then modeled in 6 (six) different fine contents ($\phi$<0.074mm), there are approximately 30%, 40%, 50%, 60%, 70% and 80%, while the original fine content will represent the nearest above mentioned percentage. The geotechnical laboratory tests in order to obtained the engineering and mechanical properties of the proposed clay core materials were carried out.

Analyses were also made on 3 (three) different base width of upstream and downstream filter, they are; 2.00, 4.00 and 6.00 m, while width of upstream filter on the top of the dam was defined at 2.00 m.

Statistical analysis on rock fill dams with central core which experience hydraulic fracturing has been studied (Fell et al 2004). They found and stated that the dams with ratio of height of the dam (H) against base width of the clay core (W) more than 2 (H/W >2) were much more likely will experiencing with hydraulic fracturing, while if (1 < H/W < 2) were more likely will experiencing with hydraulic fracturing. Analyses of the effect of upstream slope of clay core and maximum height of dam with no hydraulic fracturing were carried out based on their criteria.

Based on the finding by (Fell et al 2004), the height limitation of the rock fill dam safely from hydraulic fracturing were analyzed. Two (2) models of rock fill dam with ratio of the height of the dam (H) against the base width of the core (W), namely (H/W) were 2.00 and 2.50. These two models were considered as rock fill dam which much more likely will experiencing with hydraulic fracturing. The dam was modeled to have an upstream slope 1V : 2H, while the downstream slope was 1V : 1.75H. The crest of the dam was defined at 10.00 m, while the freeboard was 3.00 m. Figure 1 show the typical model of the dam analyzed.

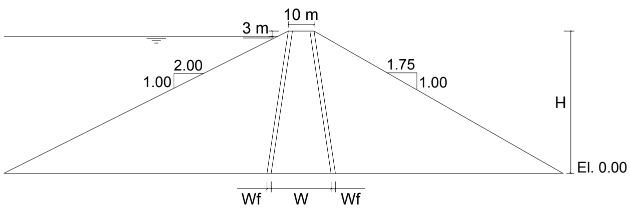


Figure 1. Typical model of the dam analyzed.

In order to investigate the effects of the upstream filter which may reduce the arching effect in the upstream face of clay core, three (3) different base width of upstream filter will also analyze.

## 3 ANALYSIS

Analyses of hydraulic fracturing using numerical analyses were carried out using finite element method. Couple analysis between deformation & stress, and seepage was adopted. The similar method has been successfully used by Cavounidis & Hoeg (1977), Naylor et al (1988), Alonso et al (1988) and Ng & Small (1999). This method was adopted considering that the hydraulic fracturing recorded mostly occurred on the first reservoir filling. The selection of soil model on the stress and deformation analyses is very important, since its represent the actual condition and control the accuracy of calculation results. In the dam construction, the embankment materials were compacted layer by layer to form the final dam configuration. In this case the non linear elastic hyperbolic soil model suits the embankment process, where the elastic modulus was formulated as function of the confining pressure, so at every loading step the magnitude of the elastic modulus will be increased accordingly. The high order elements which consist of 8 nodal points of quadrilateral and 6 nodal points of triangular were used in the element discretization. The final effective stresses resulting from the couple analyses then will be used to evaluate whether the hydraulic fracturing was occurred. The evaluation steps described as follows;

- The vertical effective stresses along upstream face of the clay core obtained from couple analysis ($\sigma_y$') compared to the hydraulic pressure due to the maximum water level in the reservoir ($\sigma_w$),
- In case the vertical effective stress at certain point less than the hydraulic pressure ($\sigma_y$'< $\sigma_w$), the tension stress was occurred at those points,
- In the case the tension stress at certain point less than the tensile stress at failure obtained from the hydraulic fracturing test at the laboratory, there were no hydraulic fracturing may occurred,
- In the case the tension stress at certain point along the upstream face of clay core greater than tensile stress at failure obtained from the hydraulic fracturing test at the laboratory, the hydraulic fracturing was occurred on that point (Djarwadi, 2010).

## 4 PRELIMINARY ATTEMPS

The preliminary attempt of hydraulic fracturing analysis was carried out on the Hyttejuvet dam in Norwegia which experienced hydraulic fracturing (Kjaernsli and Torblaa 1968). Figure 2 and 3 shows the typical cross section and element discretization for finite element analysis of Hyttejuvet dam. The embankment dam modeled in 14 step loadings to represent the construction time of Hyttejuvet dam which reported in 520 days within 2 consecutive years.

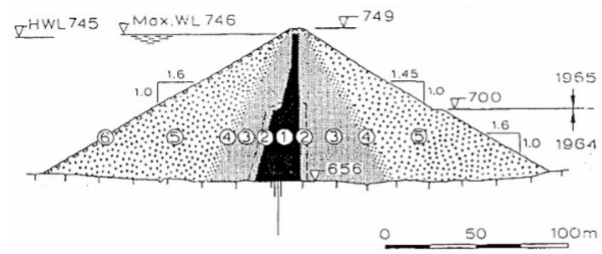


Figure 2. Typical cross section Hyttejuvet dam.

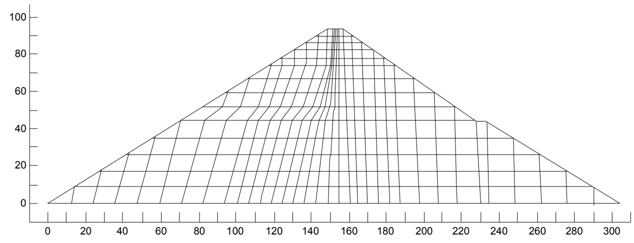


Figure 3. Element discretization of Hyttejuvet dam.

The hyperbolic and shear strength parameters of the clay core and filter were obtained from triaxial unconsolidated-undrained test results using calculation method developed by Duncan et al 1980. The soil model for rock fill embankment materials was linear-elastic (Covarrubias 1969). Hydraulic fracturing analyses of modeled Hyttejuvet dam using finite element were carried out in two steps, they are;

a. First step, the stress & deformation analysis using 14 step loadings from first layer until completion of the dam was carried out.
b. Second step, the final stress & deformation on the first step used as the initial stress & deformation on the coupling analysis between stress & deformation and seepage analysis.

The hydraulic fracturing analysis on the modeled Hyttejuvet dam in term of plotting the vertical effective stresses and hydraulic pressure was presented on Figure 4.

Figure 4 indicated that from elevation +723 m up to +742 m, the vertical effective stresses on the upstream face of the clay core were less than the hydraulic pressure of the reservoir water level. This condition indicated that the hydraulic fracturing may occur on that area, and this condition was similar to the actual location of the occurring hydraulic fracturing (Kjaernsli and Torblaa 1968).

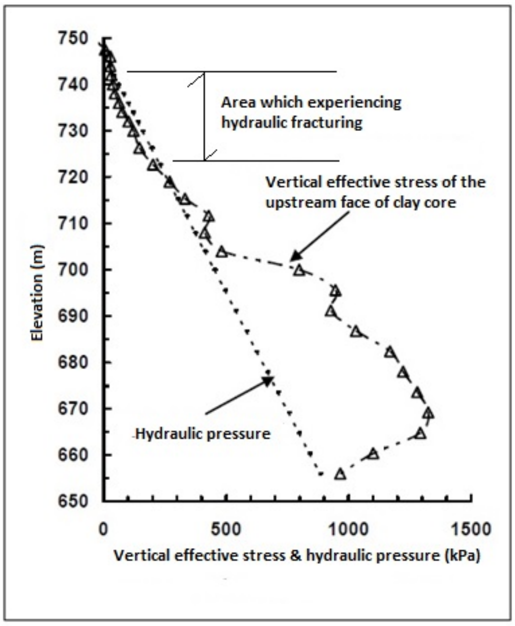


Figure 4. Position of hydraulic fracturing on Hyttejuvet dam.

With references to the accuracy of the hydraulic fracturing analysis result on the modeled Hittejuvet dam, the numerical analysis of hydraulic fracturing using finite element with coupling between stress & deformation and seepage will be used in analyzing the maximum height of the dam with no hydraulic fracturing.

## 5 ANALYSIS RESULTS

Since in the preliminary attempt gave a good accuracy in the analysis results, the similar method was adopted in the analyses of the maximum height of dam with no hydraulic fracturing at ratio of clay core of H/W = 2.00 and H/W = 2.50. The element discretization for analyses the maximum height of rock fill dam with no hydraulic fracturing shown in Figure 5.

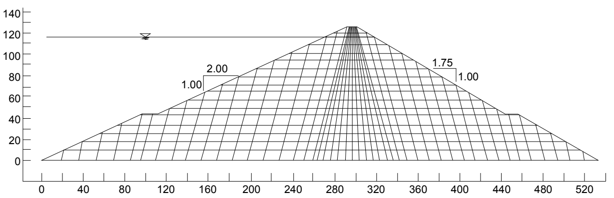

Figure 5. Element discretization of modeled dam for height limitation analysis.

The procedure of the analysis can be described as follows;

a. The analyses started at the height of dam at 100.00 meter, upstream face of clay core at H/W = 2.00, and a series of analyses on the 30% of fine contents from various dams with the base width of filter at 2.00 m were carried out.
b. In the case the analyses results indicated no hydraulic fracturing, the hydraulic fracturing analyses continued by increasing the height of dams by increment of 5.00 meter.
c. In the case at a certain height, analysis indicated that one of the dam experiencing hydraulic fracturing, the analysis on that dam then refined by reducing the height of dam at increment 1.00 meter, until the dam was free from hydraulic fracturing.
d. The minimum height of the dams with no hydraulic fracturing on the 30% of fine contents of clay core and base width of filter from Batubulan, Batutegi, Pelaparado, Sermo and Wonorejo dam, then described as upper limit of the dam with no hydraulic fracturing.
e. The similar procedure described from (a) to (d) above, then used in analyses the maximum height of the dam with no hydraulic fracturing on 40%, 50%, 60%, 70% and 80% of fine contents of clay core materials from 5 different dams.
f. The maximum height of the dams with no hydraulic fracturing on the various fine contents and base width of filter at 2.00 m analyses results plotted on a chart representing the relationship of the maximum heights of dams with no hydraulic fracturing and percentage of fine contents on the base width of filter at 2.00 meter.
g. The similar procedure described from (a) to (f) above then used to analyses the maximum height of dams with no hydraulic fracturing on the base width of filter at 4.00 m and 6.00 m.
h. The similar procedure described from (a) to (g) above will be used to analyses the maximum height of dams with no hydraulic fracturing on the ratio of H/W = 2.50.

The analyses results of the maximum height of dams with no hydraulic fracturing on the rock fill dams with upstream slope of the clay core at H/W = 2.00 and H/W = 2.50, and variation on different fine contents of clay core materials and base width of the upstream filter is presented on the charts as shown on Figure 6.

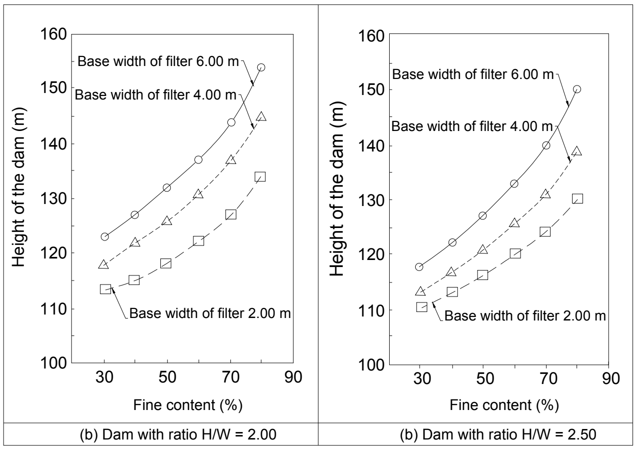


Figure 6. Relationship between the height of dams with no hydraulic fracturing on various fine contents and base width of filters.

## 6 CONCLUSION

The numerical analyses of hydraulic fracturing using finite element method by coupling the stress & deformation and seepage analysis to investigate the effects of the slope of the upstream clay core and the height of the rock fill dam has been presented. The conclusions are summarized as follows;

a. The rock fill dams modeled with steeper slope on the upstream side of the clay core, which represented by the greater ratio of height of dam against base width of the clay core have higher potential hydraulic fracturing to occur.
b. The rock fill dams modeled with wider base width of upstream filter can be constructed higher with no hydraulic fracturing to occur, comparing with the narrower upstream filter.
c. The rock fill dams modeled with greater percentage of fine contents on the clay core can be constructed higher with no hydraulic fracturing.
d. The rock fill dams modeled with ratio of height of dam against base width of clay core at H/W = 2.00, can be constructed safely against hydraulic fracturing up to the height of 155 meter.
e. The rock fill dams modeled with ratio of height of dam against base width of clay core at H/W = 2.50, can be constructed safely against hydraulic fracturing up to the height of 140 meter.

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