DIMENSION EFFECTS OF UPSTREAM FILTER OF ROCKFILL DAM AGAINST HYDRAULIC FRACTURING

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ABSTRACT

Hydraulic fracturing can occur on the upstream face clay core of the rockfill dam in case the vertical effective stress is reduced to levels that are small enough to allow tension fracture to occur. This situation may arise if the total stress in the core is reduced by arching effect where the core settles relative to the rock fill. 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 clay core. The upstream filter may reduce the arching effect, since they can bridge the great different of the stiffness of core and rockfill embankment materials. The dimension of the upstream filter may take the role in the reducing of the arching effects. This paper presents part of the hydraulic fracturing research on the rockfill dams using numerical analysis. The aim of this study is to investigate the dimension effect of the upstream filter against hydraulic fracturing. The study was carried on the configuration of the Hyttejuvet dam in Norway which experiencing hydraulic fracturing during the first impoundment. Numerical analyses using finite element methods on the Hyttejuvet dam model with various dimension of the upstream filter were carried out. The soil model for core and filter embankment was non-linear hyperbolic, while the soil model of rockfill embankment was linear-elastic. The couple analyses between stress-deformation and seepage were carried out in order to model the increasing pore water pressure in the core. The analyses were carried on the model with no upstream filter, and various width of the upstream filter from 2.00 to 10.00 meter at the foundation, while the width on the crest dam was 2.00 meter for all models. The results indicated that arching effect occur almost at all upstream face of the core if there is no upstream filter was installed. Further analyses indicated that the arching effect decrease when the upstream filter was installed, where the thicker dimension of the upstream filter greatly reduced the arching effect on the core. In the model with 6.00 meter thickness of filter, the locus of the arching effect was similar with the hydraulic fracturing on the Hyttejuvet dam as reported by Torblaa & Kjaernsli [1], and in the model with 10.00 meter thickness of filter, there was no arching effect occurred on the core of the Hyttejuvet dam. This results indicated that the dimension of the upstream filter control the arching effect to the core

Keywords: Arching effects, finite element method, hydraulic fracturing, upstream filter.

1. INTRODUCTION

Arching effect on the rockfill dams occurs in the case the total stress on the upstream face was less than its overburden pressure. Observation by Lofquist [2] indicated that the total stress at Holle and Harspranget dams in Norwegia only 50% of their overburden pressure. Kulhawy and Gurtowsky [3] analyzed the possibility of the hydraulic fracturing on the rockfill dams due to load transfer, while Cavounidis and Vaziri [4] analyzed the influence of the plasticity of the embankment materials on the load transfer. The slope of the abutments also influenced the arching effect. Zhang and Du [5] indicated that on the abutment slope of 1V : 0.5H the total stress measured only 0.52 of their overburden pressure, while on the slope of 1V : 0.85H, the total stress was only 0.74. Zu and Wang [6] analysed the influence of the arching effect to the hydraulic fracturing of rockfill dams, and found that the increasing of the stiffness or Poisson's ratio and widening the base of the core will reduce the arching effect. Hydraulic fracturing occurs on the first impoundment. The records of the dams experience with hydraulic fracturing (Table 1) indicated that the rate of embankment and impoundment did not affected to hydraulic fracturing.

Table 1. Dam experience with hydraulic fracturing

Dam	Height (m)	Construction period (year)	Impounding rate (m/month)
Balderhead	48	4	2
Hyttejuvet	90	1	20
Viddalsvatn	70	1	11
Teton	93	2	27
Yard's Creek	24	3	7

Dams with longer construction period allows the greater consolidation comparing to the shorter period, while slower impounding rate allow the wetting and development of the flownet comparing to the faster impounding rate. This situation leads to the conclusion that the arching effect on the upstream core of the rockfill as the main caused of the hydraulic fracturing. The three aspects which may influence the magnitude of the arching effects are:

a. The difference of the stiffness between the rockfill and clay core embankment materials,

b. The clay core configuration, and

c. The slope of the abutments.

One of the techniques to reduce the arching effects is to construct the upstream filter with moderate stiffness in order to bridge the large different of the stiffness between clay core and rockfill embankment materials. In this case the dimension and gradation of the upstream filter shall be designed and calculated carefully in order to meets the requirements.

2. MODELING THE DIMENSION AND GRADATION OF UPSTREAM FILTER

The analyses of upstream filter in order to reduce arching effects which may leads to the hydraulic fracturing was carried out using finite element methods. Couple analyses between deformation and stress and seepage analyses are adopted. The similar methods were used previously by Cavounidis and Hoeg [7], Ghaboussi and Kim [8], Naylor et al [9], Alonso et al [10], and Ng and Small [11]. The final stresses obtained from construction periods will be used as initial stresses during embankment periods. This method was adopted considering that the hydraulic fracturing recorded mostly occurred on the first impoundment. The selection of soil model on the stress and deformation analyses is very important. The soil model shall represent the actual condition and control the accuracy of calculation the results. In the dam construction, the embankment materials 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 increasing of the embankment will influence the magnitude of the elastic modulus (E). The elastic modulus will be corrected at every loading step. In the non linear elastic hyperbolic soil model, the elastic modulus was formulated in the confining pressure (σ_3) function, so at every loading steps the magnitude of the elastic modulus will be increased accordingly. The analyses of the upstream filter will be carried out in the configuration of the Hyttejuvet dam which experience with hydraulic fracturing. Fig 1 shows the typical cross sectionof the Hyttejuvet dam, while Fig 2 shows the gradation of the dam embankments.

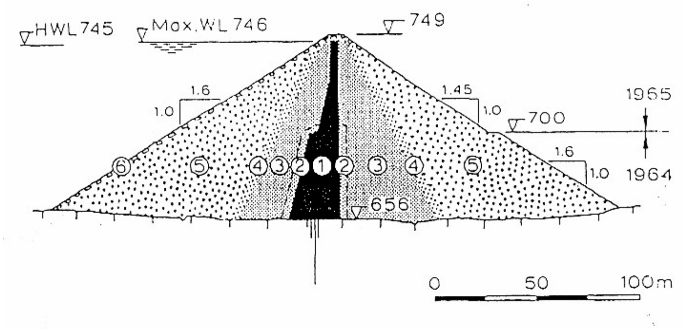


Figure 1. Typical cross section of the Hyttejuvet dam

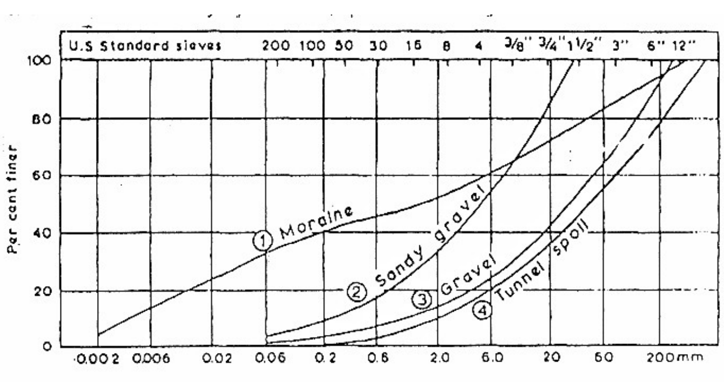


Figure 2. Gradation of the Hyttejuvet dam embankment materials

The high order elements which consists 8 nodal points of quadrilateral and 6 nodal point triangular were used in the element discretization. The dam embankment were modelled in 14 step loadings to represent the construction time of the Hyttejuvet dam which reported in 520 days within 2 consecutive years. Fig 3 shows the element discretization of the Hyttejuvet dam.

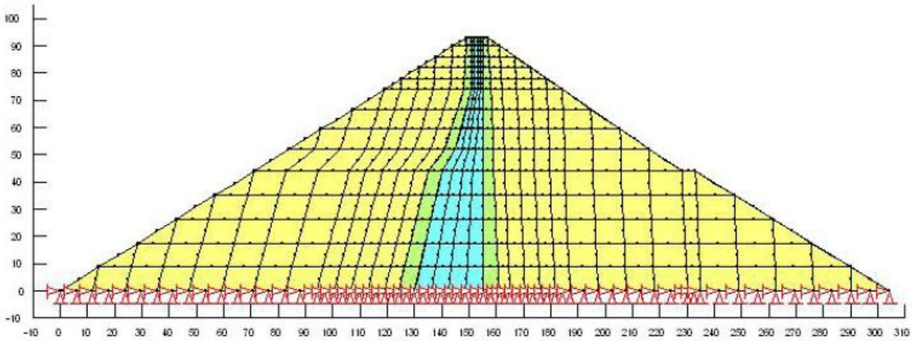
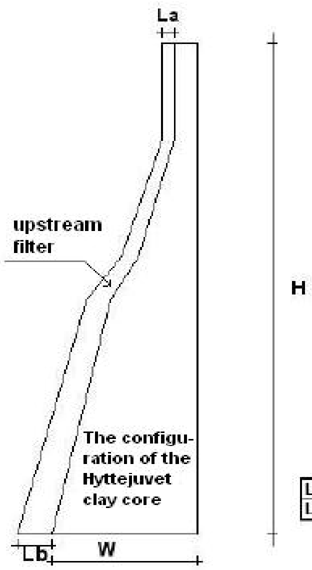


Figure 3. Element discretization of the Hyttejuvet dam.

The gradation of the clay core (1), upstream and downstream filter (2) as shown in Fig 1 were modelled using common soils and sand-gravel to follow the gradation of the Hyttejuvet dam as shown in Fig 2, while for transition zone (3), rockfill (4) and rip rap were modelled into one embankment zone. The triaxial unconsolidated-undrained with measurement of volume change were carried out in order to obtained the hyperbolic and geotechnical parameters of the clay core and filter embankment zones. The elastic modulus of the clay core at the range of 1,600 up to 4,000 kPa depends on the water contents, while the elastic modulus of the filter was at the range of 11,000 up to 15,000 kPa (Djarwadi, [12]). The rockfill zone was modelled as linear elastic material with elastic modulus of 50,000 kPa.

In order to obtained the development of the arching effects along the upstream clay core, the dimension of the upstream filter were modelled into 6 variations as shown in Fig 4. The first model assumed there was no filter installed between the clay core and rockfill embankment zones. The second up to sixth models shows gradually the increasing the base width of the upstream filter from 2.00 m up to 10.00 m, while the top width of the filter was kept in 2.00 m.



	upstream filter dimensions					
	1	2	3	4	5	6
La	0,00	2,00	2,00	2,00	2,00	2,00
Lb	0,00	2,00	4,00	6,00	8,00	10,00

Fig 4. The variation of the upstream filter dimension.

3. ANALYSES RESULTS AND DISCUSSION

The analyses of the upstream filter in order to reduce the arching effects which may leads to hydraulic fracturing can be carried out using finite element method, using couple analyses between stress and deformation and seepage analyses. The couple between SIGMA/W and SEEP/W of the Geostudio software or developed the own computer codes can be adopted.

The hyperbolic and shear strength parameters of the clay core and filter can be obtained from triaxial unconsolidated-undrained test results using calculation method developed by Duncan et al [13]. The soil model for rockfill embankment materials was linear-elastic, follow the method used by Covarrubias [14]. Tabel 2 shows the hyperbolic and shear strength parameters for clay core and filter, while Table 3 shows the parameters of the rockfill zone. During the couple analyses, a set of material properties such as hydraulic conductivity and water content functions, ratio between horizontal against vertical hydraulic conductivity as well as the direction of flow shall be inputted to the program.

Table 2. Hyperbolic and shear strength parameters of clay core and filter

Material	Hyperbolic parameters						Shear strength		Unit weight
	K	N	K_{ur}	K_b	m	R_f	ϕ (°)	C (kPa)	γ_b (kN/m^3)
Clay core	316.87	-0.116	380.44	181.74	-0.07	0.828	20.91	74.60	18.38
Filter	659.32	0,519	727.09	377.62	0.282	0.712	43.3	0	19.63

Table 3. Linear-elastic parameters for rockfill

Material	Elastic Modulus (kPa)	Poisson ratio (ν)	Unit weight (kN/m^3)
Rockfill	50,000	0.30	22.00

The first step of the analyses was to carry out the stress and deformation during dam construction, in 14 step loadings, and second step, the final stresses obtained from the first analyses will be used as initial stresses in the couple analyses. The final stresses results from couple analyses then will be used to evaluate whether the hydraulic fracturing was occurred. The evaluation to the final stresses obtained from couple analyses described as follows;

a. The effective stress along upstream face of the clay core obtained from couple analyses (σ_y') then compared to the hydraulic pressure due to the maximum water level in the reservoir (σ_w),

b. In case the effective stress at a certain points less than the hydraulic pressure ($\sigma_y' < \sigma_w$), the tension stress was worked at those points,

c. In the case the tension stress at a certain points along the upstream face of the clay core less than the ultimate tensile stress obtained from hollow cylinder tests (Djarwadi [12]), there were no hydraulic fracturing,

d. In the case the tension stress at a certain points along the upstream face of the clay core greater than the ultimate tensile stress obtained from hollow cylinder tests (Djarwadi [12]), the hydraulic fracturing will occurred.

The analyses results presented on the charts comparing the effective stress (σ_y') and hydraulic pressure (σ_w) acting on the upstream face of the clay core shown on Fig. 5. In the first attempts, there was assumed no filter installed between rockfill and clay core. Fig 5 shows that hydraulic fracturing occurs at almost at all upstream face. This situation indicates that the great difference of the stiffness between embankment materials reduced the total as well as effective stresses at the upstream face of the clay core due to arching effects. When the filter embankment zone was installed between rockfill and clay core embankment materials with moderate stiffness to bridge the different of their stiffness, the area which affected by arching effects were reduced as shown in Fig 5 b, c, d, e and f. When the base width of the filter embankment zone was increased, the arching effects on the lower parts of the upstream face of clay core were reduced. This situation proved that the dimension or configuration of the filter zone may reduce the arching effect which may leads to the hydraulic fracturing in the rockfill dams.

In the analyses with 6.00 m base width of filter, the location of arching effects which lead the hydraulic fracturing in the model of Hyttejuvet dam was similar to the actual location of hydraulic fracturing on the Hyttejuvet as shown on the report by Kjaernsli and Torblaa [1].

When the base width of the filter increased to 8.00 m or 10.00 m, there was no arching effect which may leads to the hydraulic fracturing along the upstream face of the model of Hyttejuvet dam. The arching effects were reduced to the levels that not causing hydraulic fracturing.

In the modern dam engineering, where the finite element method become a common tools for numerical analyses, the design of the dimension of the upstream filter in terms of gradation and dimension may be adopted in order to reduce the arching effect which may leads to the hydraulic fracturing in the rockfill dams. In this case the couple analyses should be used in order to accommodate the increasing the pore water pressure in the core due to the water level of the reservoir.

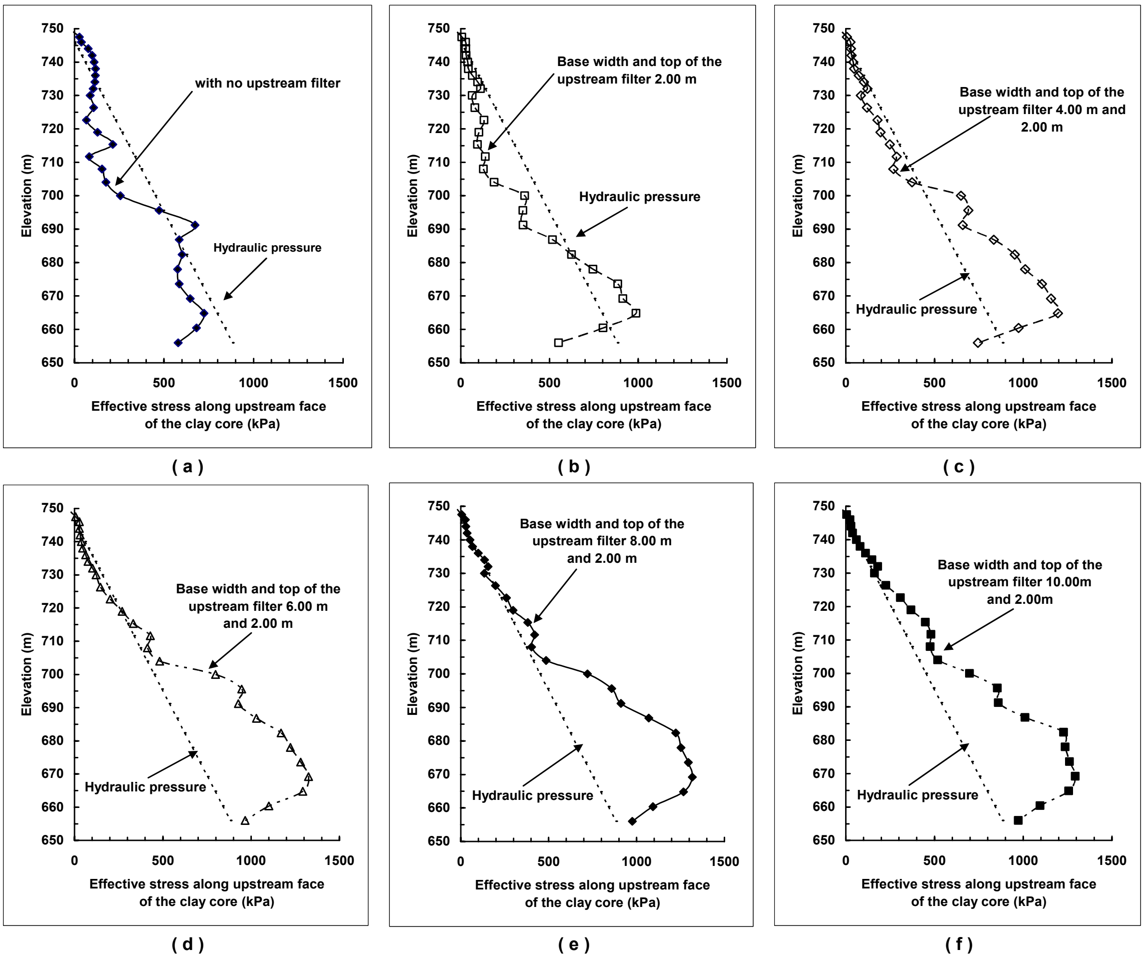


Fig 5. Analyses result of the variation filter dimension against hydraulic fracturing

4. CONCLUSSION

The dimension effects of the upstream filter of the rockfill dam against hydraulic fracturing have been presented, the numerical analyses of the case was carried out using finite element method. The couple analyses between stress and deformation and seepage analyses were applied. Six (6) variation of the upstream filter dimensions were analyses in order to obtained the development of the arching effects as well as the possibility of hydraulic fracturing occurred on the upstream face of the clay core. The followings conclusions are derived from the analyses results:

a. The upstream filter can be used as an alternative to reduce the arching effects which may lead to the hydraulic fracturing in the rockfill dams,

b. Proper design of upstream filter in terms of the gradation and dimension are required in the rockfill dam engineering,

c. The finite element analyses using couple analyses between stress and deformation and seepage analyses can be used as an numerical analysis methods in the design of the upstream filter,

d. The full stability analyses of the dam shall be carried out after the dimension of the upstream filter was fixed in order to effects of the filter dimension to the overall stability of the dam.

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