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EFFECTS OF UPSTREAM SLOPE OF CLAY CORE AND HEIGHT OF THE ROCK FILL DAMS AGAINST HYDRAULIC FRACTURING

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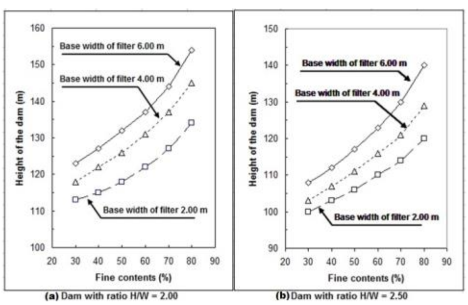
Graphical abstract



(a) Dam with ratio H/W = 2.00 (b) Dam with ratio H/W = 2.50

Abstract

Hydraulic fracturing in rock fill dams may occur in case where the upstream face of the clay core experiencing tension cracks due to the arching effects and water pressure from the reservoir. One of the causes of arching effects was the steep slope of the upstream clay core. A statistical research on the dam experiencing with hydraulic fracturing indicated that rock fill dams with un-compacted rock fill embankment zone with narrow and steep slope of core, where the ratio between height against base width of core > 2 were considered much more likely for hydraulic fracturing to occur, while if the ratio was between 1 to 2 were considered likely to occur. This paper investigates the height limitation of the rock fill dams on the ratio of the height against the base width of core of 2.00 and 2.50, which represent the conditions of more likely and much more likely hydraulic fracturing to occur. The clay cores were obtained from five (5) major dams in Indonesia; Batubulan, Batutegi, Pelaparado, Sermo and Wonorejo dams, where their heights vary from 37 m to 125 m. The variation of the clay core embankment materials was made in six (6) various fine contents, and compacted at their optimum moisture contents. Analysis was made on the modeled rock fill dam using finite element analysis with coupling of the stress, the deformation and the seepage analyses. The hydraulic fracturing may occur in case the vertical effective stresses in the upstream face of clay core were less than the water pressure from the reservoir. The results indicated that the maximum dam height with no hydraulic fracturing was governed by the percentage of fines in the clay core and the ratio of the height to the base width of the clay core. The clay core that consists of more fine contents, and smaller ratio of height against the base width of the clay core of the dam has greater resistance against hydraulic fracturing.

Keywords: Hydraulic fracturing; numerical analysis; coupling analysis

1.0 INTRODUCTION

Arching effect on the rock fill dams occurs 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 Norway were reported that the total stress in only 50% of their overburden pressure [1]. The possibility of hydraulic fracturing on the rock fill dams due to load transfer between embankment zones has been analyzed and reported [2]. 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% [3]. The influence of arching effect to the hydraulic fracturing of rock fill dams were analyzed [4], and found that the increasing of the stiffness or Poisson's ratio and the widening the base width of the clay core will reduce the arching effect [4]. 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 [5]. Table 1 shows the dams experiencing hydraulic fracturing, where the embankment and reservoir impounding rates did not affect to the occurring of hydraulic fracturing [6]. 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 cause of hydraulic fracturing in the rock fill dams is mainly due to the arching effect.

2.0 MODELING THE DAM

Statistical analysis on rock fill dams with central core which experience hydraulic fracturing has been studied [7]. They found 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 would experience with hydraulic fracturing [7]. Analyses of the effect of the upstream slope of clay core and the maximum height of dam with no hydraulic fracturing were carried out based on their criteria.

In order to accommodate their criteria [7], two models of rock fill dams were generated 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.

In order to investigate the effects of the clay core materials and upstream filter to the hydraulic fracturing, a variation on the clay contents of the clay core which represent by the percentage of the fine content and the base width of the upstream filter was modeled.

Analyses were made in 6 (six) various fine contents of clay core, they are; 30%, 40%, 50%, 60%. 70% and 80%, obtained from 5 major dams in Indonesia, they are; Batubulan, Batutegi, Pelaparado, Sermo and Wonorejo dams.

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

The model dam had an upstream slope 1V: 2H, while the downstream slope was 1V:1.75H. The crest of the dam was defined at 8.00 m, while the freeboard was 3.00 m. Figure 1 shows the modeled dam as described above.

Table 1 Dam experiencing with hydraulic fracturing [6]

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

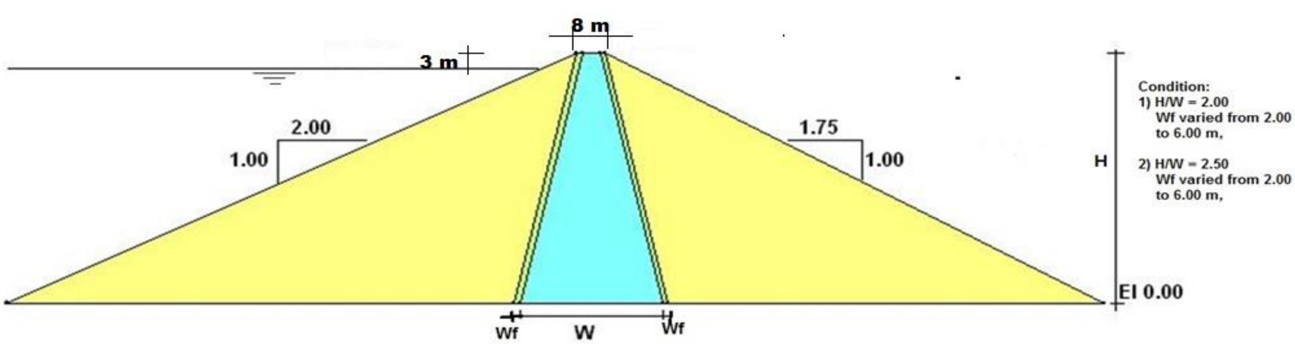


Figure 1 Modeled dam for analyzing the effects of upstream clay core slope and height of dam against hydraulic fracturing

2.1 Preliminary Attempt

Preliminary attempt in hydraulic fracturing analyses was carried out in order to validate and compare the analysis results with the actual condition on site, the suitability of the software analysis and method. The software used in the analysis was Geostudio 2007, Finite element analysis with coupling of the stress & deformation and seepage analyses was adopted. The similar method was used previously [8], [9], [10], [11], and [12].

The selection of the soil model in the hydraulic fracturing analysis on rock fill dam is very important, since the soil model shall represent the actual condition and control the accuracy of the results of the analysis. The non-linear elastic hyperbolic model was selected [13]. In non-linear elastic hyperbolic soil model, the elastic modulus was formulated as function of the confining pressure, so at every loading step the magnitude of the elastic modulus increased accordingly. In the dam construction, the embankment materials were placed and compacted layer by layer to form the final dam configuration. In this case the non-linear elastic hyperbolic soil model suits the embankment process.

The preliminary attempt of hydraulic fracturing analysis was carried out on the hydraulic fracturing [14]. Figure 2 and 3 shows the typical cross section and gradation of the embankment material of Hyttejuvet dam. The element discretization of the Hyttejuvet dam is shown in Figure 4. The high order elements which consist of 8 nodal points of quadrilateral and 6 nodal point triangular were used in the element discretization. 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.

The hyperbolic and the shear strength parameters of the clay core and the filter were obtained from triaxial unconsolidated-undrained test results using calculation method of [15]. The model for the rock fill embankment materials was linear-elastic [16]. Table 2 shows the hyperbolic and the shear strength parameters for clay core and the filter, while Table 3 shows the parameters of the rock fill materials.

Hydraulic fracturing analyses of modeled Hyttejuvet dam using finite element were carried out in two steps, they are;

1) The stress & deformation analysis using 14 step loadings from first layer until completion of the dam was carried out.

2) The final stress & deformation on the first step were used as the initial stress & deformation on the coupling analysis between stress & deformation and seepage analysis.

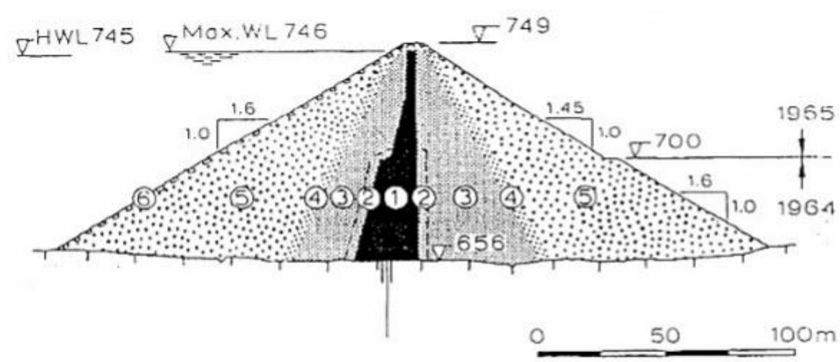


Figure 2 Typical cross section of Hyttejuvet dam [14]

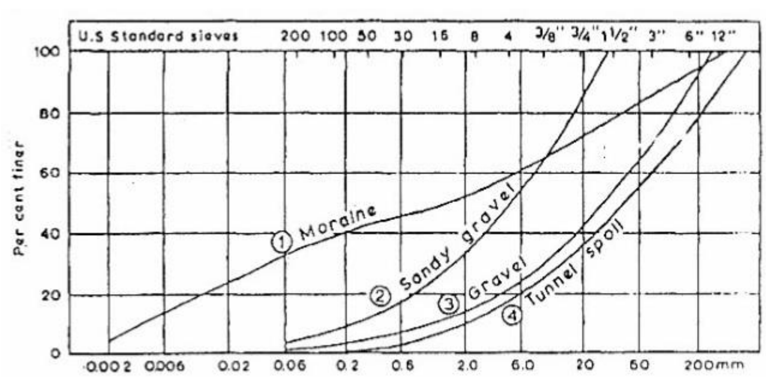


Figure 3 Gradation of the Hyttejuvet dam embankment materials [14]

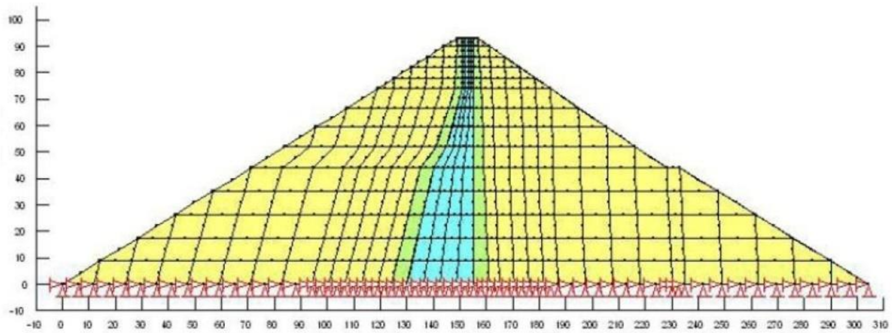


Figure 4 Element discretization of the Hyttejuvet dam

Table 2 The hyperbolic and the shear strength parameters of the clay core and the filter

Material	Hyperbolic parameter						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	43.30	0	19.63

Table 3 The parameters of the rock fill materials

Material	Elastic modulus (kPa)	Poisson Ratio (ν)	Unit weight (kN/m^3)
Rock Fill	50,000	0.30	22.00

The vertical effective stresses on the upstream face of the clay core were then used to evaluate whether the hydraulic fracturing would occur or not.

The evaluation to the vertical effective stresses along the upstream face of the clay core was carried out as follows;

a. The vertical effective stress along the upstream face of the clay core obtained from the coupling analysis was plotted together with the maximum hydraulic pressure generated by the water in the reservoir.
b. In the case the vertical effective stresses at certain points were less than the hydraulic pressure, the tension stress may occur.
c. In the case the tension stresses at certain points at the upstream face of clay core were less than the tension stresses at failure of the same materials obtained from hollow cylinder test in the laboratory, hydraulic fracturing would not occur [17].
d. In the case the tension stresses at certain points at the upstream face of the clay core were greater than the tension stresses at failure of the same materials obtained from hollow cylinder test in the laboratory, hydraulic fracturing would occur [17].

The hydraulic fracturing analysis on the modeled Hyttejuvet dam in term of plotting the vertical effective stresses and hydraulic pressure is presented in Figure 5.

Figure 5 indicates that from elevation +723 m up to +742 m, the vertical effective stresses on the upstream face of the clay core are less than the hydraulic pressure of the reservoir water level. This condition indicates that the hydraulic fracturing may occur on that area, and this condition is similar to the actual location of the occurring hydraulic fracturing [14].

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

The ratio of H/W = 2.00, which consider as dams with more likely will experience with hydraulic fracturing, and H/W = 2.50, which consider as dams with much more likely will experience with hydraulic fracturing were analyzed with the same method.

3.0 ANALYSES OF THE MAXIMUM HEIGHT OF THE DAMS

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 ratios of clay core of H/W = 2.00 and H/W = 2.50. The element discretization for the analyses of the maximum height of rock fill dam with no hydraulic fracturing is shown in Figure 6. The hyperbolic parameters, the shear strength and the bulk density are presented in Table 4.

The procedure for the analysis can be described as follows:

i. The analyses started at the height of dam at 100.00 meter, upstream face of clay core of ratio H/W = 2.00, and series of analyses for the 30% of fine content from various dams with the base width of filter at 2.00 m were carried out.
ii. In the case the analyses results indicated no hydraulic fracturing, the hydraulic fracturing analyses continued by increasing the height of dams by the increment of 5.00 meter.
iii. 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 of 1.00 meter, until the dam was free from hydraulic fracturing.
iv. The minimum height of the dams with no hydraulic fracturing for the 30% of fine content of the clay core and the base width of the filter from Batubulan, Batutegi, Pelaparado, Sermo and Wonorejo dams, then described as upper limit of the dam with no hydraulic fracturing.
v. The similar procedure described from (a) to (d) above, was then used in the analyses of the maximum height of each dam with no hydraulic fracturing for 40%, 50%, 60%, 70% and 80% of fine content of the clay core materials for five (5) different dams.

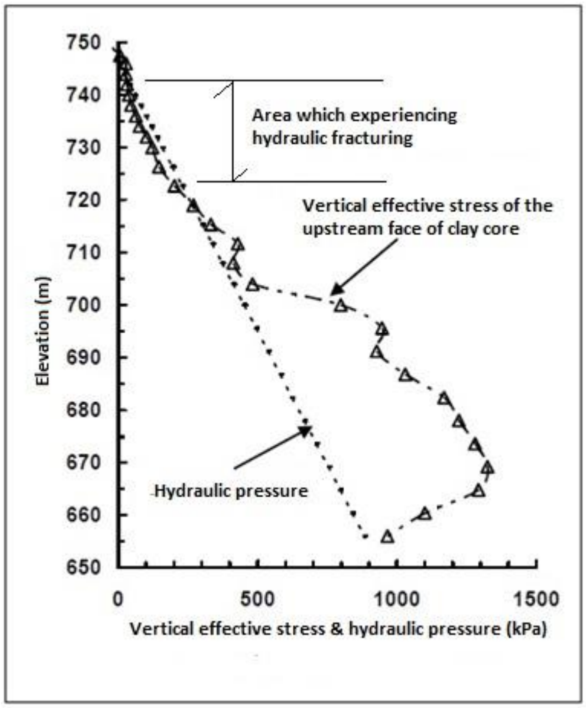


Figure 5 Position of the hydraulic fracturing occurrence for the modeled Hyttejuvet dam

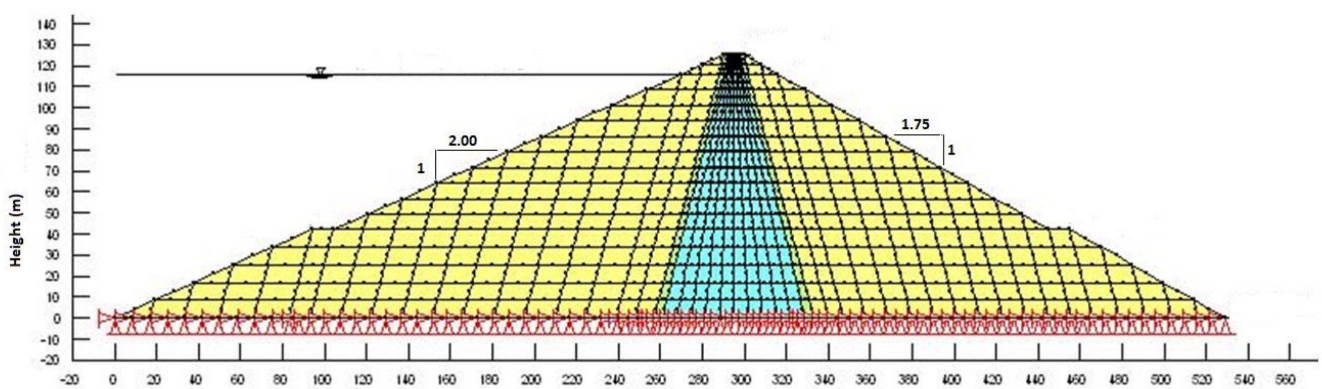


Figure 6 Element discretization of modeled dam for analyzing the maximum height of the dam with no hydraulic fracturing

vi. The maximum heights of the dams with no hydraulic fracturing for various fine contents and base width of filter of 2.00 m analyses results were plotted on a chart representing the relationship of the maximum heights of dams with no hydraulic fracturing and percentage of fine contents.

vii. The similar procedure described from (a) to (f) above then used to analyse the maximum height of dams with no hydraulic fracturing for the base widths of the filter of 4.00 m and 6.00 m.

viii. The similar procedure described from (a) to (g) above was then used to analyse the maximum height of dams with no hydraulic fracturing for the ratio of H/W = 2.50.

The results of the analyses of the maximum height of each dam 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 for different fine contents of the clay core materials and the base widths of the upstream filter are presented on in Figure 7.

Table 4 Hyperbolic and shear strength parameters of clay core for various percentages of fine contents

Material	Fine content (%)	Hyperbolic parameters						Shear strength		Unit weight
		K	n	K_{ur}	K_b	m	Rf	ϕ (°)	c (kPa)	γ_b (kN/m³)
Batubulan dam	30	357.02	-0.116	428.43	229.56	-0.089	0.92	18.15	78.20	18.38
	40	332.95	-0.033	399.54	185.03	-0.036	0.97	17.71	85.10	18.49
	50	329.93	0.072	395.92	180.00	0.064	0.95	16.21	88.30	18.55
	60	277.24	0.187	332.69	173.00	0.086	0.96	14.31	90.10	18.73
	70	261.05	0.245	313.26	145.17	0.145	0.91	13.35	95.50	18.80
	80	212.41	0.329	254.89	112.29	0.163	0.94	11.46	103.70	18.98
Batutegi dam	30	428.16	-0.231	513.79	318.21	-0.255	0.83	24.49	62.40	20.16
	40	389.15	-0.120	466.98	256.62	-0.160	0.87	23.51	72.40	20.28
	50	364.64	0.054	437.57	244.63	-0.091	0.88	21.87	76.00	20.10
	60	308.48	0.133	370.17	181.92	0.045	0.90	19.31	80.10	19.50
	70	273.07	0.242	327.68	163.58	0.081	0.88	18.29	84.30	19.35
	80	231.28	0.356	277.54	124.68	0.168	0.94	17.55	88.80	18.84
Pelaparado dam	30	369.96	-0.160	433.95	278.23	-0.247	0.94	22.22	72.00	19.80
	40	332.43	-0.081	398.95	242.05	-0.188	0.93	20.63	74.70	19.77
	50	280.64	0.095	330.77	190.81	-0.081	0.93	18.64	83.50	19.47
	60	268.21	0.256	321.85	170.89	-0.037	0.93	15.29	89.70	19.25
	70	235.59	0.281	282.71	135.07	0.066	0.92	14.70	90.30	18.95
	80	227.11	0.305	129.80	129.80	0.123	0.95	13.21	98.20	18.69
Sermo dam	30	289.17	-0.143	347.00	243.60	-0.215	0.88	18.74	76.00	18.43
	40	265.53	-0.046	318.64	218.20	-0.161	0.90	17.26	79.00	18.18
	50	238.13	0.028	285.76	165.46	-0.053	0.87	17.31	86.30	17.86
	60	222.49	0.073	266.99	156.82	-0.033	0.93	14.32	93.50	18.08
	70	180.03	0.164	216.04	136.26	0.068	0.93	12.51	94.80	17.89
	80	160.15	0.236	192.18	121.83	0.133	0.90	10.62	108.70	18.15
Wonorejo dam	30	348.02	-0.129	417.12	283.81	-0.238	0.92	19.20	72.70	19.22
	40	331.99	-0.069	398.39	274.23	-0.182	0.96	17.91	74.70	19.14
	50	278.22	0.011	333.86	235.96	-0.120	0.90	15.70	81.00	18.91
	60	264.20	0.067	317.04	219.74	-0.077	0.94	18.04	90.40	18.91
	70	189.35	0.229	227.22	142.85	0.068	0.95	14.10	97.40	18.46
	80	132.46	0.383	158.95	107.36	0.169	0.90	13.98	100.50	18.29

4.0 CONCLUSION

The numerical analyses of the hydraulic fracturing using finite element method by coupling the stress and the deformation and the seepage analysis for the investigation of the effects of the slope of the upstream clay core and the height of the rock fill dam has been presented. The conclusions are summarised 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 the height of the dam against the base width of the clay core have higher potential of hydraulic fracturing to occur.

(b) The rock fill dams modeled with the wider base width of the upstream filter can be constructed higher with no hydraulic fracturing to occur, compared with the narrower upstream filter.

(c) The rock fill dams modeled with greater percentages of fine contents of the clay core can be constructed higher with no hydraulic fracturing.

(d) The rock fill dams modeled with the ratio of the height of dam against the base width of the clay core at H/W = 2.00, can be constructed safely against hydraulic fracturing up to the height of 155 m.

(e) The rock fill dams modeled with the ratio of the height of the dam against the base width of the clay core at H/W = 2.50, can be constructed safely against the hydraulic fracturing up to the height of 140 m.

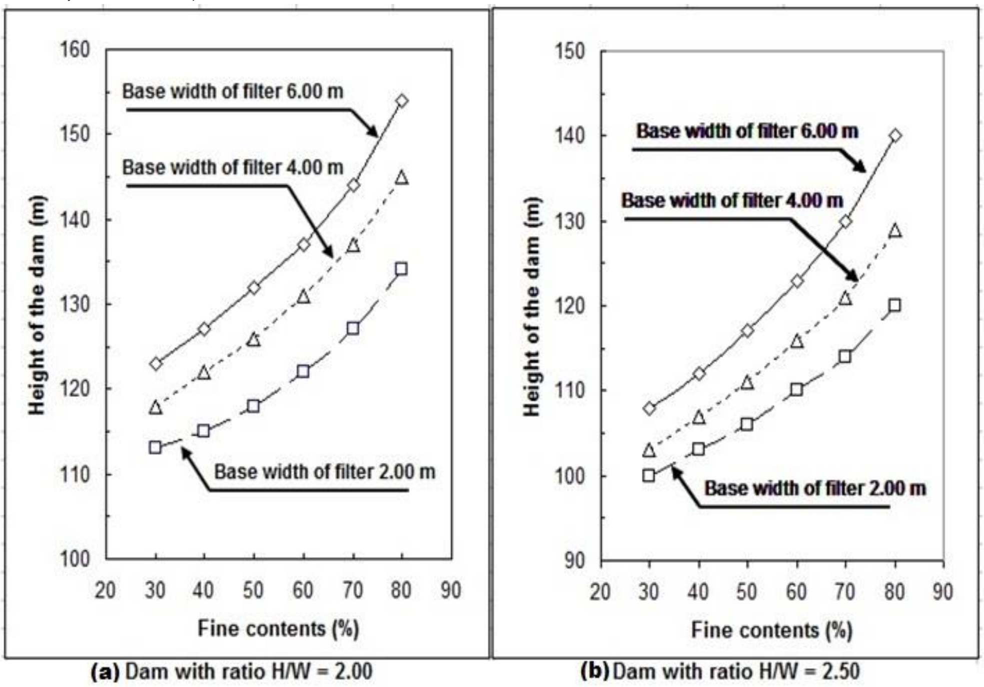


Figure 7 Relationship between the height of dams with no hydraulic fracturing on various fine contents and base width of filters

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