THE EFFECT OF RESERVOIR WATER LEVEL FLUCTUATION TO THE SEEPAGE ON EARTH DAM

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ABSTRACT

The modeling of earth dam was carried out in a drainage and seepage tank to analyze the seepage resulting from water level fluctuation in the upstream of the dam. The dam models were made of the mixture of Mt. Merapi sand deposit with the soil of sandy-silt from Wonosari area. The variations of sand content in the mixture were 100%; 90% and 80% and the upstream slope inclinations were 1:1; 1:1.5 and 1:2. The result showed that the dams with more sandy-silt in the mixture have smaller seepage and the dams with steeper upstream slope have greater seepage. During rapid rising of water level, the dams with steeper upstream slope have a high rising rate of upstream water level and higher height of downstream slope failure. Moreover, during rapid drawdown, the dams with gentler upstream slope have a smaller rate of upstream drawdown and lower height of upstream slope failure. The dams with more sandy-silt in the mixture have a higher value of rising rate and drawdown of upstream water level but lower height of downstream and upstream slope failure. In the dam management, continuous monitoring of the seepage resulting from reservoir water level fluctuation is required to avoid dam failure.

Keywords: Earth dam, rapid rising, rapid drawdown, seepage, slope failure.

1 INTRODUCTION

In addition to its significant benefits, earth dams contain potential hazard that may threaten people and the environment. Thus, special treatment in dealing with dams, starting from the design, construction and the management phases is required. An earth dam failure took place on March 27, 2009 at 04.30 WIB, where the middle part of Situ Gintung embankment and spillway collapsed causing flash flood that took more than 100 lives. Situ Gintung, built in 1933 by the Dutch Government, is located on the volcanic deposit rock (Fathani, 2011). The hydrology physical phenomenon indicated that a day before the collapse significant rainfall intensity of 162 mm/day and 80 mm/day occurred in 1.5 hours. This caused the reservoir water level to rise in a very short time (Legono et.al, 2009a).

The mechanism of the collapse of the earth dam is highly related to the fluctuation of water level and its interaction to the soil material of the dam body (Fathani and Legono, 2011; Legono et.al, 2009b). Hence, analyzing the effect of the rising and lowering of reservoir water level to the seepage on the earth dam by considering the water level fluctuation, dam slope inclination and the type of soil composing the dam body is necessary. The objective of this study is to analyze the seepage and failure mechanism in an earth dam structure caused by reservoir water level fluctuation by using a physical model experiment.

2 SEEPAGE AND EARTH DAM STABILITY

One of the causes of slope failure was the increase in pore water pressure (Hardiyatmo, 2006). The rising of water level at the upstream of an earth dam may cause seepage pressure to downstream and increase pore water pressure causing the soil shear strength to decrease. Whereas the drawdown of upstream water level results in the increase of pore water pressure in the dam body and the seepage pressure to the upstream. Seepage in an earth dam may occur in either the dam body or foundation due to the permeable characteristic of the soil. Soil permeability is defined as a soil characteristic to pass up fluid flow through the pore cavity, and water flow in the soil is called seepage (Das, 1997). The resistance of the flow depends on the soil type, granular size, soil mass density, and the geometrical shape of the pore cavities.

Casagrande (1937) suggests an analytical approach to calculate seepage based on different water level at upstream and downstream, slope inclination, hydraulic gradient and permeability of the soil. Phreatic line can be made with analytic method or graphically by drawing a flownet. Seepage modeling through a numerical simulation may be carried out using the *SEEP/W* program. Input parameters used in this analysis were the model geometry and the soil data for the dam model such as grain size, void ratio, unit weight and permeability coefficient.

A dam may undergo damage or collapse when the occurring seepage exceeds the limit. Rapid rising of upstream water level may cause a significant seepage pressure inside the dam body and reduce the stability of the downstream slope. An earth dam becomes saturated when the upstream water level is high or seepage occurs at the downstream slope. When rapid drawdown takes place, the soil stability is in critical condition. Such condition may endanger the upstream slope of the dam (Fathani and Legono, 2010).

3 RESEARCH METHOD

3.1 Materials and Instruments

The modeling used the sand from Mt. Merapi as the main material. The sand passed sieve number 10 (2 mm) and was retained on sieve number 200 (0.075 mm). As the mixture material, sandy-silt from Wonosari area which passed sieve No. 4 (4.75 mm) was used. The materials for all dam models were a mixture of sand and sandy-silt with three variations, i.e. 100% sand; 90% sand and 10% sandy-silt; and 80% sand and 20% sandy-silt with similar unit weight of (γ) = 1,7 gram/cm^3 and various water content (*w*) of 13.08 %, 14.27 %; and 13.50 %, respectively.

The main equipment used in this research was the drainage and seepage tank as presented in Figure 1. Valve in the pump was modified to control the rate of the upstream water level rise and drawdown.

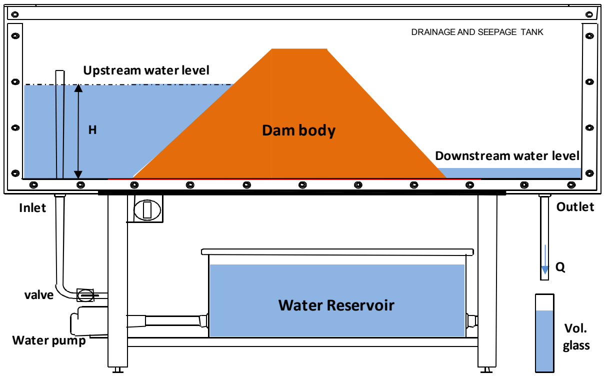


Figure 1. Sketch of seepage model experiment in the drainage and seepage tank

3.2 Research Stages

The preparation stage consisted of tests of water content, specific gravity, unit weight, grain size analysis, standard proctor, direct shear and triaxial of the soil material. The model was made in such a way into the drainage and seepage tank that the collapse process could be well observed. The sketch of the dam model is presented in Figure 2. The height was 30 cm; with a width of 10 cm; and constant downstream slope gradient (1:1). The upstream slope inclination was made in variations of 1:1; 1:1.5; and 1:2. The earth dam model with upstream slope gradient of 1:2 is presented in Figure 3.

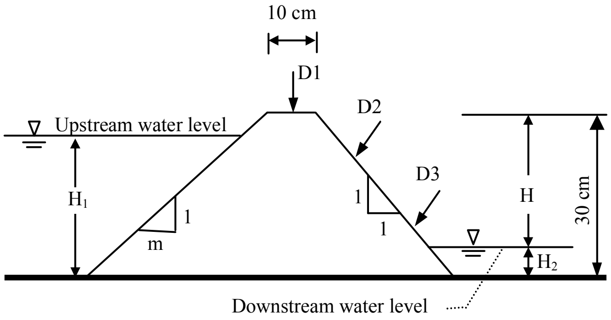


Figure 2. Front look of the model sketch

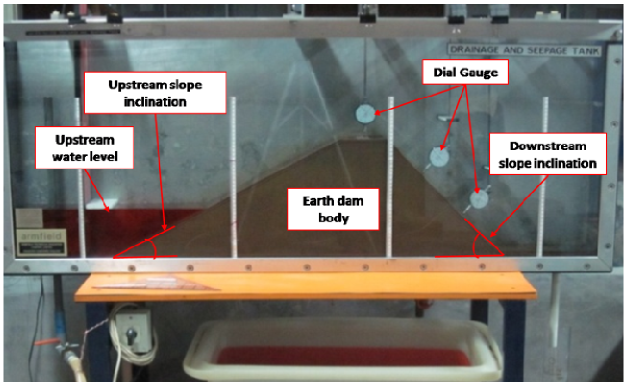


Figure 3. The earth dam model with upstream slope inclination of 1:2

3.2.1 Seepage experiment

The experiment was started by flowing the water to the upstream of the dam in a rate set by the valve. Water level rising was measured and recorded in every 15 minutes up to a stable level. Water coming out of the outlet pipe at the downstream part was measured as the seepage discharge. With the same method, the experiment was continued up to maximum water level of 250 mm or the model already indicated landslide.

Dam model made from sand material was coded “S”, and one from the mixture of 90% sand + 10% silt was coded “S_{90}” and one with 80% sand and 20% silt was coded “S_{80}“. Models with upstream slope inclination of 1:1; 1:1.5; and 1:2 were coded M_1, $M_{1.5}$ and M_2, respectively. Models with valve opening of 1, 2 and 3 were coded 1, 2, and 3 and so on. Therefore, for example, the seepage model made from sand with upstream slope inclination 1:1 and valve opening 1 was coded “S-M_1-1”.

3.2.2 Rising and drawdown of upstream water level

The water level fluctuation was started by raising the upstream water level rapidly up to a maximum height. The rising rate was recorded with observation up to maximum water level of 250 mm. At the same time, the landslide process was observed to identify the initial failure and its mechanism. This step was done for any 5 cm change of water level elevation.

After 250 mm of water level was reached, the experiment was continued for the lowering of upstream water level (rapid drawdown). The rate of the lowering of water level was arranged using drain valve. The lowering was halted once the water level reached the minimum elevation of 1.3 cm.

The models with upstream slope inclination of 1:1; 1:1.5; 1:2 were coded with A, B and C. The experiment of water level rising was coded R; and lowering was L. For example, a model of water level rising with sand material and upstream slope inclination of 1:1 and valve opening 1 was coded S-RA1, as for the drawdown was S-LA1.

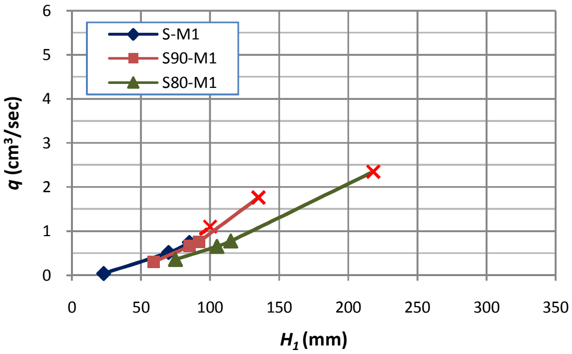
4 ANALYSIS AND DISCUSSIONS

Based on the results of experiment, the seepage discharge occurred on each model and the relation between rising and drawdown of water level and the seepage in the dam body can be analyzed. The permeability coefficient measured from the laboratory experiment was used to calculate the seepage discharge by analytical and numerical method. In addition, the influence of the rate of rapid rising/drawdown of the upstream water level to the dam slope stability can also be analyzed.

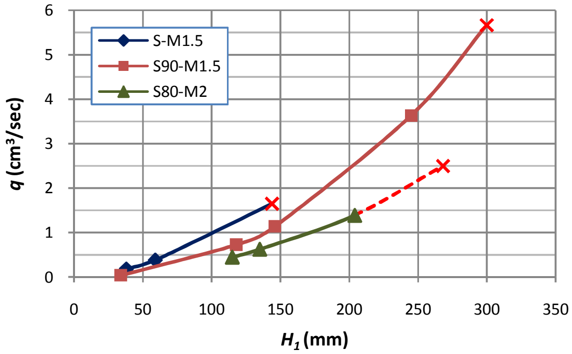
Based on the results of the preliminary soil tests, it can be identified that the soil was sandy silt with high plasticity while the results of soil mixture (silt-sand) would be used to analyze the seepage discharge. Soil parameter that would be used to analyze the seepage are void ratio, grain size analysis and permeability coefficient. Void ratio for sand = 0.862; for mixture sand 90% + silt 10% = 0,848; and mixture sand 80% + silt 10% = 0.816, whereas the coefficient of permeability for sand = 0.0020987 cm/sec; mixture sand 90% + silt 10% = 0.0017459 cm/sec; and mixture sand 80% + silt 10% = 0.0014007 cm/sec.

4.1 Results of Seepage Experiment

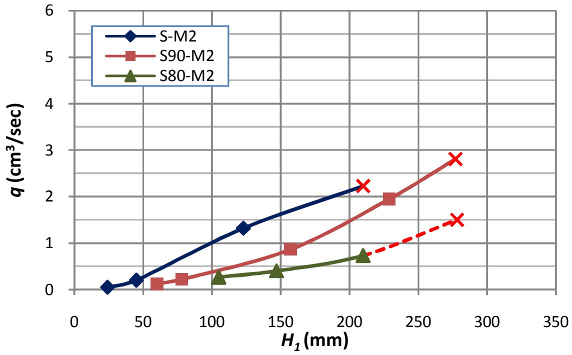
Based on the result of the seepage experiment, the relation between the seepage discharge and the upstream water level can be determined. Seepage discharge would rise in accordance with the increase of the upstream water level. Figure 4 shows that the seepage discharge (q) tended to increase in accordance with the increase of upstream water level (H_1). At the same upstream slope inclination ($slope_{upstream}$), seepage in dams with soil mixture tended to have smaller discharge.



(a) Dam model with $slope_{upstream}$ 1:1



(b) Dam model with $slope_{upstream}$ 1:1.5



(c) Dam model with $slope_{upstream}$ 1:2

X failure at toe of downstream slope --X-- downstream slope failure

Figure 4. The relation of seepage discharge (q) by experiment and the upstream water level (H_1)

The seepage experiment was carried out by using the simulation up to the downstream slope which experienced collapse. For S model with $slope_{upstream}$

1:1, it was stopped for model S-M_1-4 with H_1 = 100 mm and q = 1.100 cm^3/sec because the downstream slope had already collapsed. For S_{90}, it stopped for S_{90}-M_1-4 with H_1 = 135 mm and q = 1.759 cm^3/sec because the downstream slope had experienced landslide. Moreover, for PS_{80}, it stopped at S_{80}-M_1-4 with q = 2.344 cm^3/sec and H_1 = 218 mm. For models with upstream slope gradient of 1:1.5 and 1:2, the same simulation was carried up to the downstream slope experienced collapse.

This explains that seepage discharge, besides being affected by their composing material, was also affected by the inclination of the upstream slope. The more silt added in the mixture, the smaller the *q* would be. Similarly, the larger the slope inclination, the smaller the discharge at the downstream of the dam.

4.2 Seepage Analysis by Analytical and Graphical (*Flow-net*)

The analysis of seepage discharge in the dam by analytical/graphical method was carried out using the permeability coefficient resulteing from the laboratory test. Figure 5 presents the comparison between seepage discharges from the analytic/graphic and experimental results.

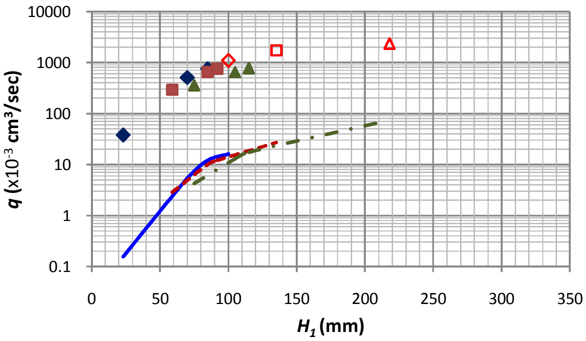
In Figure 5a, the dam model with upstream slope gradient ($slope_{upstream}$) 1:1 and upstream water level (H_1) = 100 mm, the largest q resulting from the analytic/graphic occurred at model S-M_1 of 0.016 cm^3/sec > S_{90}-M_1 (0,015 cm^3/sec) > S_{80}-M_1 (0.012 cm^3/sec). The q resulting from the experiment in model S-M_1 = 1.100 cm^3/sec was significantly higher than that of analytic/graphic, and so was with model S_{90}-M_1 and S_{80}-M_1. For dam model with $slope_{upstream}$ 1:1.5 and 1:2 (Figure 5b and Figure 5c), they tended to have the same tendency with $slope_{upstream}$ 1:1 where q experiment was larger than q analytic/graphic.

4.3 Analysis of Seepage by Using the Numerical Simulation

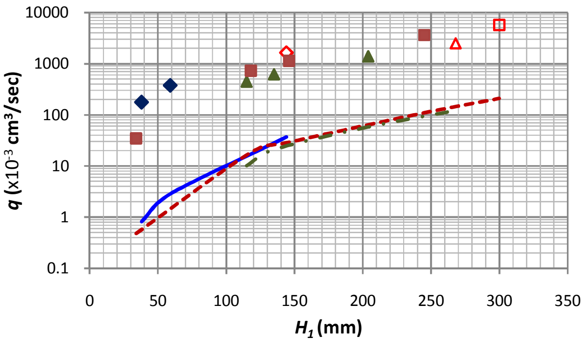
The numerical simulation by using *SEEP/W* program was carried out considering the soil parameters resulting from the laboratory test. The seepage discharge (q) of the dam model resulting from the *SEEP/W* analysis is presented in Figure 6.

In Figure 6a, for the dam model with $slope_{upstream}$ 1:1 and H_1 = 100 mm, the largest q at S-M_1 = 0.022 cm^3/sec > S_{90}-M_1 (0.0215 cm^3/sec) > S_{80}-M_1 (0.021 cm^3/sec), and q resulting from the experiment of model S-M_1 = 1.100 cm^3/sec was so much larger than q by numerical simulation and so was the model S_{90}-M_1 and S_{80}-M_1. For dam model with $slope_{upstream}$ 1:1.5 and 1:2 (Figure 6b and Figure 6c), it showed the same tendency as dam model with $slope_{upstream}$ 1:1.

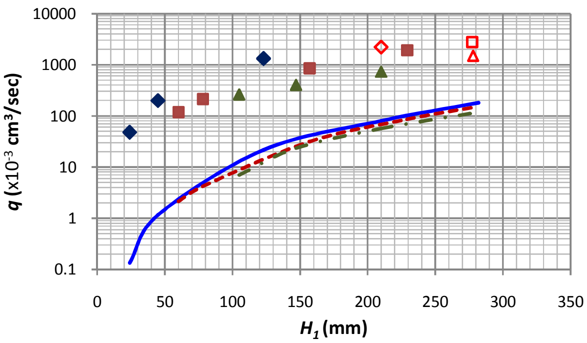
Figure 7 presents the relation between seepage discharge (q) resulting from the experiment, analytic/graphic (Casagrande) and numerical simulation of *SEEP/W* to the upstream water level (H_1).



(a) Dam model with $slope_{upstream}$ 1:1



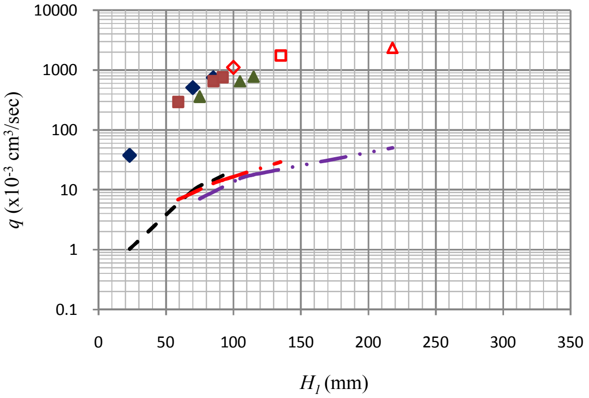
(b) Dam model with $slope_{upstream}$ 1:1.5



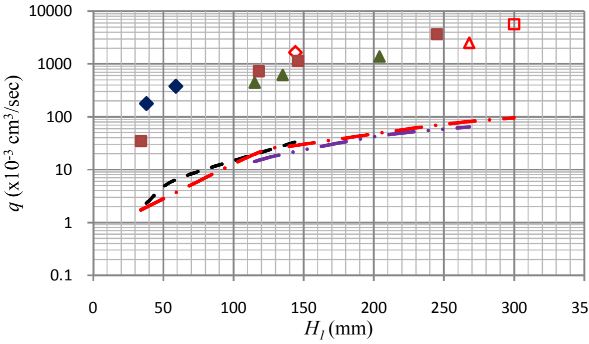
(c) Dam model with $slope_{upstream}$ 1:2

Figure 5. The relation of seepage discharge (q) by analytic/graphic and upstream water level (H_1)

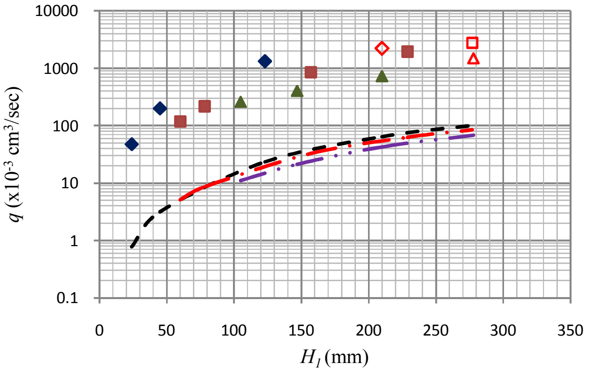
Analysis and experiment results showed that q tended to increase in accordance with the rising of the upstream water level. In the same upstream slope inclination ($slope_{upstream}$), q in the sand model with silt addition showed smaller discharge due to the smaller permeability resulting from the silt addition. The seepage on the dam model with $slope_{upstream}$ that was slanted tended to have smaller q than with steeper $slope_{upstream}$.



(a) Dam model with $slope_{upstream}$ 1:1

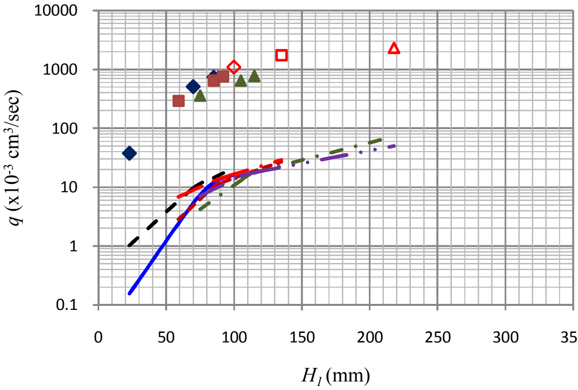


(b) Dam model with $slope_{upstream}$ 1:1.5

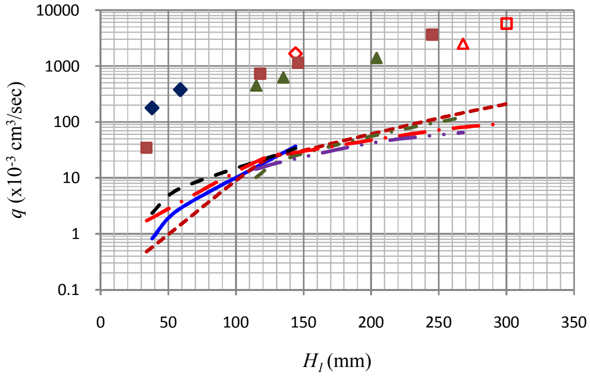


(c) Dam model with $slope_{upstream}$ 1:2

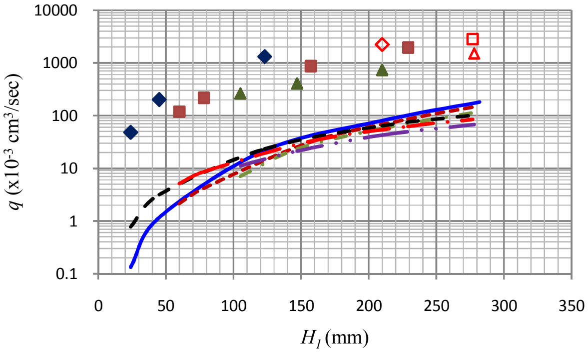
Figure 6. Relation of seepage discharge (q) resulted from numerical simulation and upstream water level (H_1)



(a) Dam model with $slope_{upstream}$ 1:1



(b) Dam model with $slope_{upstream}$ 1:1.5



(c) Dam model with $slope_{upstream}$ 1:2

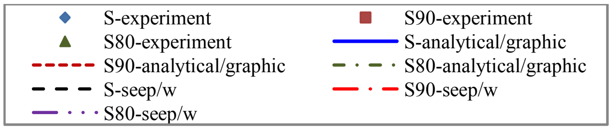


Figure 7. Relation between seepage discharge (q) and upstream water level (H_1) of all models

In the analytic/graphic and numerical simulation, the model was assumed in homogeneous and isotropic condition with seepage flow as steady-state flow. In overall, q resulting from the numerical simulation was smaller than the analytic/graphic. For q resulting from the experiment was so much larger than that from analytic/graphic and numerical simulation because an ideal model in the laboratory (homogeneous, isotropic and steady-state flow) is more difficult to make. In addition, the big difference in q was also due to the significant seepage passing though the interface between the ground model and wall and the drainage and seepage tank base that could not be measured during the experiment.

4.4 Upstream Water Level Fluctuation

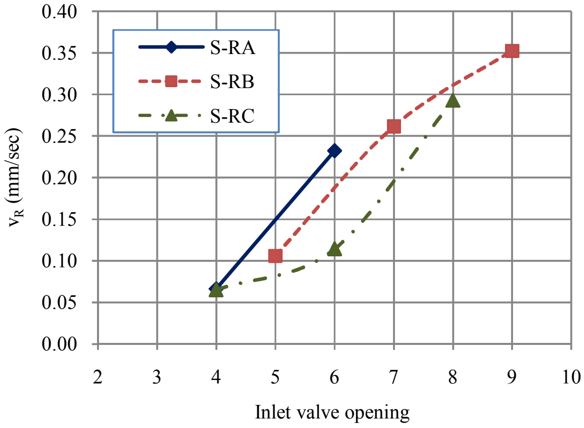
4.4.1 Rapid rising of the water level

The rapid rising of water level was carried on by increasing the upstream level up to 250 mm maximum. The landslide was indicated by deformation of soil granule in line with the additional water level at the upstream. In Figure 8, the rate of rising at the upstream (v_R) of all earth dam models is presented.. All dam models showed the same tendency where v_R more dominantly affected the downstream slope landslide. By larger v_R, $h_{downstream}$ was also higher.

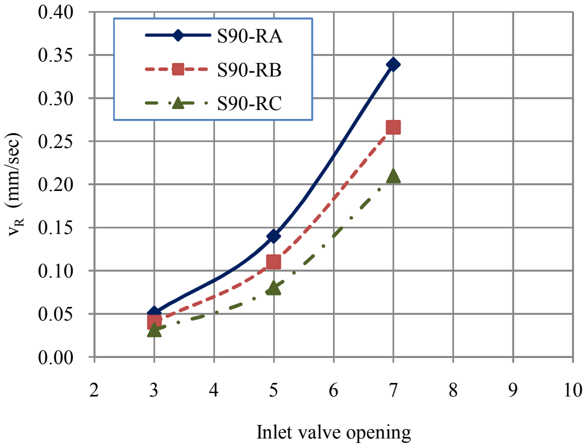
Figure 9 shows the relation between the rising rate of upstream water level (v_R) with downstream slope landslide height ($h_{downstream}$) for all earth dam models. v_R and $h_{downstream}$ were also affected by the upstream slope inclination ($slope_{upstream}$) in which the dam model had $slope_{upstream}$ that was smaller (steeper) with larger v_R and higher $h_{downstream}$. On the contrary, larger $slope_{upstream}$ (slanted) showed smaller v_R and lower $h_{downstream}$. Dam models with more silt as the material, showed larger v_R but lower $h_{downstream}$. On the contrary, models with smaller content of silt showed smaller v_R and higher $h_{downstream}$.

4.4.2 Rapid drawdown of water level

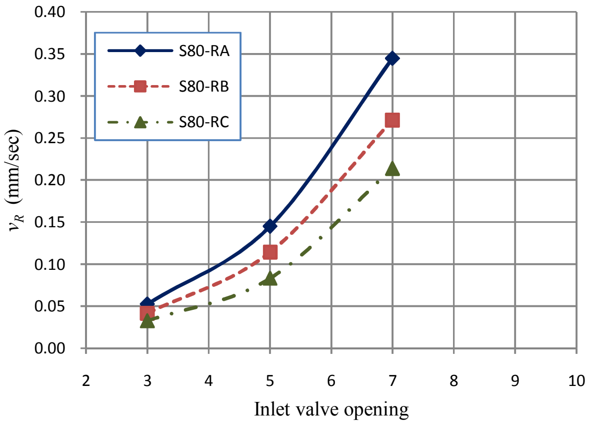
Rapid drawdown experiment was carried out after the filling of water to the upstream part was 250 mm and then its height is deducted rapidly up to the maximum height of 13 mm. Based on the observation, the landslide was started with the movement of soil granules on the slope surface and followed by continual erosion process causing landslide at the upstream slope. The above process was so fast and directly proportional to the rate of water lowering. In Figure 10, the rate of drawdown of upstream water level (v_L) and the height of the landslide ($h_{upstream}$) of all models are presented. All models had the same tendency that the higher $h_{upstream}$, the higher $h_{upstream}$ (v_L) would be. Dam model with larger v_L , would have higher $h_{upstream}$.



a) Dam model of 100% sand



b) Dam model of 90% sand + 10% silt

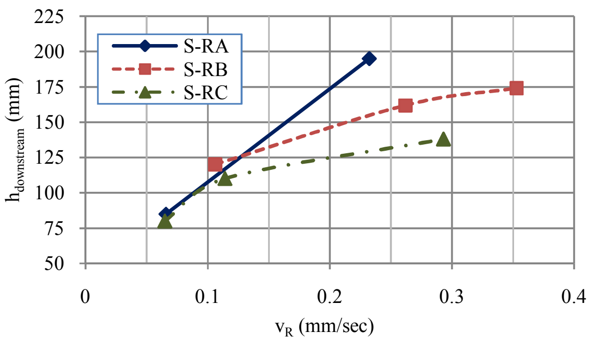


c) Dam model of 80% sand+ 20% silt

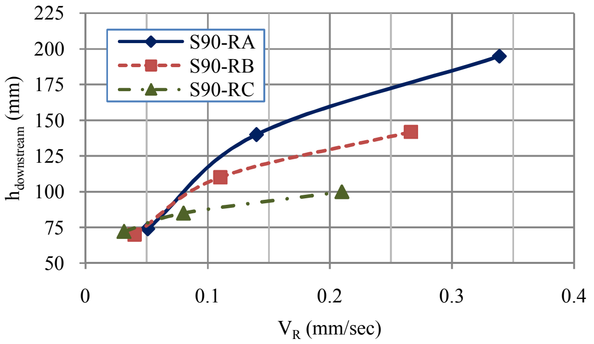
Figure 8. The rising rate of upstream water level (v_R) and the landslide of downstream slope ($h_{downstream}$) for all earth dam models

Figure 11 shows the relation of the drawdown rate of upstream water level (v_L) with the height of the landslide in ($h_{upstream}$), for all models.

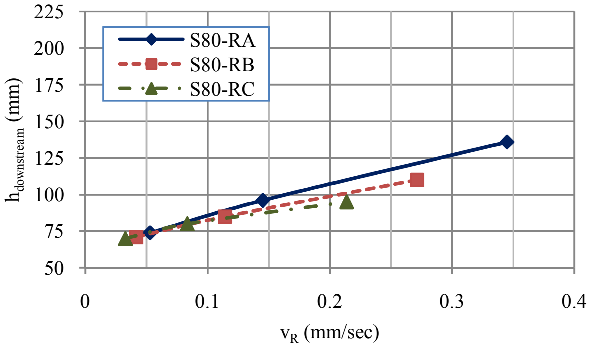
v_L dan $h_{upstream}$ were also influenced by the upstream, slope ($slope_{upstream}$) where the dam models are the same as $slope_{upstream}$ which was more slanted with smaller v_L and lower $h_{downstream}$. The other steeper dam of $slope_{upstream}$ had v_L larger and higher $h_{downstream}$. Models with more silt had the larger v_L and lower $h_{upstream}$



(a) Dam model of 100% sand



(b) Dam model of 90% sand + 10% silt



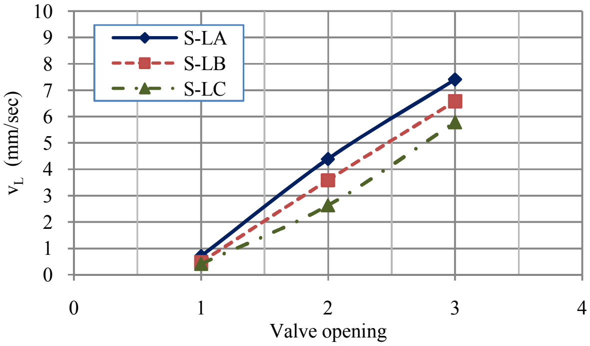
(c) Dam model of 80% sand+ 20% silt

Figure 9. The relation of v_R with $h_{downstream}$ for all earth dam models

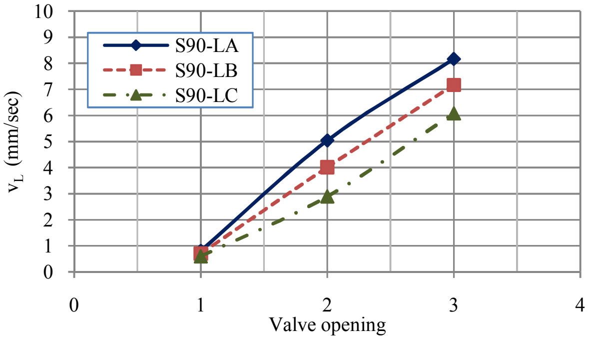
4.5 The Effect of the Water Level Fluctuation on the Dam Safety

4.5.1 The effect of rapid rising of water level

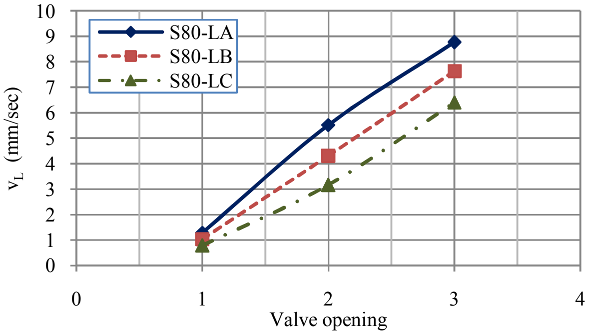
Rapid rising gave more effect to the occurrence of landslide at the downstream slope. Increasing water level at the upstream caused a large difference of water level in the upstream and downstream resulting in larger seepage pressure inside the dam body.



(a) Dam model with 100% sand

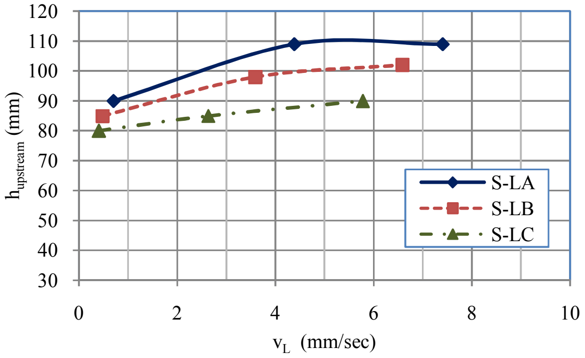


(b) Dam model of 90% sand + 10% silt

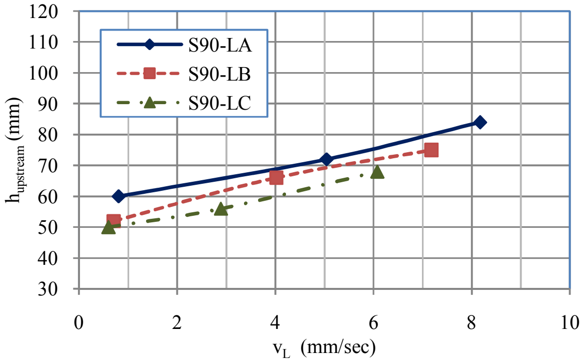


(c) Dam model of 80% sand+ 20% silt

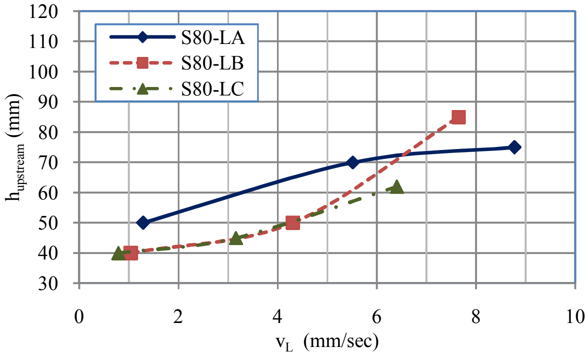
Figure 10. The lowering rate of upstream water level (v_L) and the landslide of downstream slope ($h_{downstream}$) for all earth dam models



(a) Dam model with 100% sand



(b) Dam model of 90% sand + 10% silt



(c) Dam model of 80% sand+ 20% silt

Figure 11. The relation of v_L and $h_{upstream}$ for all earth dam models

This would increase the pore pressure inside the dam body and might reduce the soil shear strength. Due to the decreasing shear strength, the upstream landslide would be indicated by cracks at the downstream toe and continue to raise water level at the upstream.

4.5.2 The effect of rapid drawdown of water level

An earth dam might be saturated when water level was high. Rapid drawdown caused the water in the pores to become slower that the soil in the dam was still filled with water and wet leading to heavier weight as there was no more pressure to upper vertical direction. In addition, the seepage flowing to the upstream due to the difference of water level in the dam body would be larger resulting in seepage pressure to the upstream direction. At such condition, the slope stability was in critical condition and potential for landslide.

4.5.3 Dam Safety

Water flowing the soil layers caused hydrodynamic pressure or seepage force (F_{hd}) working at the same direction with the flow. Hydrodynamic force is a linear function of the water volume weight (γ_w) and hydraulic gradient (i), $F_{hd} = \gamma_w i$ which affects the soil weight volume depending on the water flow direction. When the flow direction is vertically down, the effective volume weight (γ_{ef}) increases. When the direction is horizontal, the vector F_{hd} and γ' (floating volume weight) are mutually perpendicular working. When the flow direction is vertically up, F_{hd} is in the opposite direction to γ'. In such condition, when $F_{hd} = \gamma'$, soil loosens its weight and becomes unstable (critical condition), the critical hydraulic gradient (i_c) occurs and $F_{hd} = \gamma_w i_c$. When the critical condition is exceeded, $F_{hd} > \gamma'$ and γ_{ef} become negative. In this condition, the soil is lifted or floated (quick-condition). Such condition caused the fine granules to be transported to form pipes beneath the ground, called piping which may disturb the structure stability.

Based on the above description, seepage in an earth dam also experiences hydrodynamic at the same direction with its flow. Flow occurring in an earth dam is relatively horizontal so that the landslide in the downstream toe is not caused either by quick-condition or piping. Piping occurred when the flow was in vertically up direction and generally occurred at the downstream slope foot surface caused by the seepage flow passing through the dam base soil.

5 CONCLUSIONS

Based on the experiment, it can be concluded that the seepage discharge (q) was more dominantly affected by the upstream water level height (H_1) than the inclination of the upstream slope ($slope_{upstream}$). Analysis results showed that q increased in accordance with H_1. For the same $slope_{upstream}$, the dam model with more silt mixture showed smaller q and model with more slanted $slope_{upstream}$ indicated smaller q than the steeper one. Overall, q experiment was much larger than q analytic/graphic and numerical analysis because creating model in homogeneous, isotropic and steady-state flow conditions was difficult. In addition, this was also due to seepage passing through the interface between the model and the base wall of the drain and seepage tank which was unmeasured during the experiment.

The largest level of landslide in the upstream part occurred in the model with H_1 and steeper $slope_{upstream}$ (1:1). When rapid rising of upstream water level occurred, water pore pressure increased in the dam body that decreased the shear resistance of the soil and might cause landslide at the downstream slope. The dam model with steeper $slope_{upstream}$ had larger upstream water level rising velocity (v_R) and higher downstream landslide height ($h_{downstream}$). The dam model with more silt in the mixture showed larger v_R but lower $h_{downstream}$.

In rapid drawdown of the upstream water level, water in the pores would slowly dissipate in such a way that the silt was still filled with water and in wet condition. This led to the increasing weight because there was no longer pore to up direction. This increased the pressure of the water in the pore and the seepage pressure to the upstream direction became larger. The dam model with more slanted $slope_{upstream}$ had smaller velocity (v_L) of water drawdown and lower upstream slope landslide height ($h_{upstream}$). In the dam model with less silt indicated smaller v_L than one with more silt but higher $h_{upstream}$.

Based on the experiences during this research, one of the recommendations given to further research is to use observation instruments for outer and inside the dam body in order to obtain more comprehensive deformation behavior of the dam. In the compacting process of the dam model, more consistent and controlled methods are required. Dam models are to be made lengthwise on the wider media in order to obtain more accurate and significant results. The interface area between the earth dam model and wall and the base of drain and seepage tank should have been added with paste to prevent seepage from the interface area.

In the exploitation and maintenance activity of the dam, continual observation on the leakages around the dam and on the condition of the spillway is required to enable it to function well when plan flood may cause increasing water to exceed the plan water level. Likewise, observation of q at the toe of downstream slope is required to identify the seepage more quickly and to prevent the dam failure from taking place.

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