SEEPAGE MODELING IN EARTHFILL DAMS WITH VARIOUS SUBSOIL TYPES

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***Abstract**: The earthfill dam might be built for all subsoils condition, however the common problems are the seepage flow and dam stability. This study uses numerical simulation model for seepage discharge and slope stability analysis. The characteristic of the dam is obtained from Tugu Dam, Trenggalek, while the subsoil data is varied for five soil types which are clay, silty clay, silt, silty sand, and sand. The first simulation analyze certain subsoil type during various water levels, while the second simulation analyze certain water level elevation during various soil types. Each simulation will be analyzed for seepage discharge and slope stability. The first simulation results show that seepage discharge and water level elevation have a logarithmic correlation with $R^2 > 0.75$. The largest seepage discharge at 1.90×10^{-3} m^3/s is sand soil, while the smallest is clay soil at 1.47×10^{-9} m^3/s. The results of the second simulation show that the seepage discharge and saturated volumetric water content also have a logarithmic correlation. Based on these two simulations, the seepage discharge still meets the requirement since plotted below the average annual runoff, which is 1% of the 10-year re-flood discharge. The amount of re-flood discharge is calculated using the Nakayasu Synthetic Unit Hydrograph (SUH) which is 5.99 m^3/s. The safety factor of slope stability is more than 1.2 which is considered as stable dam.*

Keywords: *Earthfill dams, seepage, stability, safety factor, water level*

INTRODUCTION

An earthfill dam is constructed using compacted soil around the dam body. This dam have advantages and disadvantages, where the advantage is its ability to be constructed on any subsoil condition including unfavourable topography. However, with these advantages, the earthfill dam includes as the most failures dam in the world. With 65.6% of all dam failures on earthfill dams, 60% of those were caused by seepage in the dam body or the subsoil. In a study for the risk category for dam failure, seepage was the first causes. On a small scale, seepage will damage the function of the dam capacity because there are other outflow discharges which exceed the designed needs. On a large scale, seepage could damage the dam foundation and can even collapse the structure of the dam[1][2].

From the problems related to seepage in the subsoil type of earthfill dam, it is necessary to conduct a research study as basic reference for designing earthfill dam on various subsoil condition. The goal is to investigate the sub soil type used as a foundation for an earthfill dam. This is critical to reducing seepage discharge because of the high soil permeability value. Therefore, research is needed to determine the relationship between subsoil types, water table conditions, and seepage discharge. The allowable seepage discharge is 1% of the average annual runoff discharge. Although generally, seepage is challenging to predict accurately, numerical modeling and even physical modeling are needed to predict more accurately. In addition to seepage, it is also necessary to consider the value of dam stability. The allowable safety factor for the stability of the dam soil is 1.2 [3-5].

Several previous studies that have discussed seepage and slope stability using GeoStudio Software are: determine the effect of reservoir water level fluctuations on seepage discharge and flow patterns that occur within the dam body; determine the profile, seepage discharge, and the value of the permeability coefficient; analyze leachate seepage in clay soils including discharge and seepage velocity; and determine the water discharge in the excavated area, the number of dewatering wells, the magnitude of the uplift force at the base of the excavation area, and the value of seepage at the base of the retaining wall [6-9].

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METHODOLOGY

This study focuses on numerical simulation of the characteristics of the subsoil and reservoir water level conditions in the earthfill dam by using the GeoStudio program: seepage analysis module and stability analysis module. The seepage analysis module is used to analyze changes in pore water pressure on the dam. Meanwhile, stability analysis module can be used to calculate the safety factor for dam. The method used to calculate the seepage is a 2D finite element at steady-state conditions. The Finite Element Method (FEM) is used because it is more reliable than the limit equilibrium method [10-13].

A. PROBLEM IDENTIFICATION

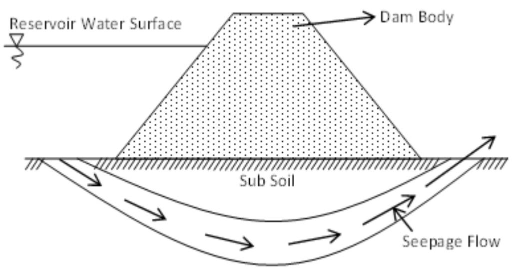

Figure 1 Seepage modeling in subsoil of earthfill dams

Problem identification is a description of the current conditions in the field, 60% of the problems that occur are caused by seepage in the soil layer under the earthfill dam. When viewed from the main cause, the seepage occurs because of the nature of water flowing from areas of high pressure to areas of low pressure through these gaps. While the gap is formed due to the gradation of the soil composition. The seepage value that occurs should not exceed a predetermined limit, because it can damage

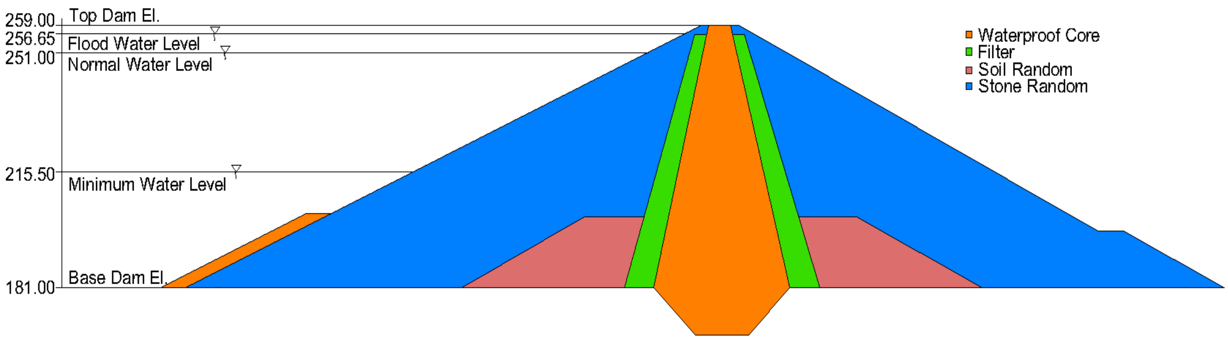

Figure 2 Dam data

the structure of the dam. Figure 1 shows the problem that will be discussed in this paper, which is a seepage in subsoil of the earthfill dam.

B. DATA COLLECTION

The data used in this study is secondary data. The secondary data including:

- Dam data, where it is used as the basis for simulation and also governs the loads for the subsoil. Soil data for the dam body is taken from A. K. Nisa' (2019) described in Table 1 and Figure 2 [14].

Table 1 Dam body soil characteristics data

No	Soil Material	Soil Type	Characteristics
1.	Waterproof core	*Clay*	Sat. VW_c = 0.69 m^3/m^3 Sat. K_x = 2.9 x 10-8 m/sec
2.	Filter	*Light Clay*	Sat. VW_c = 0.375 m^3/m^3 a = 2.7 n = 2.05 mm m = 0.36 mm Sat. K_x = 1 m/sec
3.	Soil Random	*GM*	Sat. VW_c = 0.25 m^3/m^3 D_{10} = 0.01 mm D_{60} = 6 mm LL = 35 % Sat. K_x = 0.05 m/sec
4.	Stone Random	*Gravel*	Sat. VW_c = 0.27 m^3/m^3 D_{10} = 200 mm D_{60} = 500 mm Sat. K_x = 1.5 m/sec

- Data of water level and dam elevation, where these data is used as a reference for the simulation of water conditions, these are shown in Table 2 and Figure 2.
- Subsoil Data, which is used as the basis for the subsoil condition of the dam, including saturated volumetric water content (Saturated VW_c), saturated conductivity (Saturated K_x), coefficient of volume compressibility (M_v), unit weight (γ), phi (Φ), and cohesion (c). Soil data for dam subsoil was taken from several sources, including Fredlund et al. (1994), OSU Center for Health Sciences (1996), and Aria K. Nisa' (2019). These are shown in Table 3 [14-16].
- Rainfall and Watershed Data, where these data are only used for obtaining water level through flood analysis. Afterwards, the water level is modeled into the seepage numerical analysis. This data is taken from Purwanto (2017) [17].

Table 2 Water level and dam elevation data

No	Water Level Elevation	Conditon
1.	+181	Dam base elevation
2.	+215.5	Minimum water level elevation
3.	+251	Normal water level elevation
4.	+256.65	Flood water level elevation
5.	+259	Dam top elevation

C. DATA PROCESSING

In this part, a simulation is carried out to determine the effect of differences in the dam water level on the seepage discharge. Systematically the first simulation analyzes the influence of a certain soil type varied by fluctuations in the water level of the dam every 5-meters. The elevation used as a reference is from the base elevation of the dam to the elevation of the flood water level. While the second simulation analyzes the effect of changes in soil types, which is Saturated VW_c at certain water level elevation.

D. DATA ANALYSIS

In this part, the analysis process is carried out on the data processing results. The analysis carried out to answer the problem formulation is as follows:

- Analysis of factors affecting seepage in subsoil earthfill dams.
- Analysis of the relationship between the value of saturated volumetric water content with seepage discharge and soil characteristics.
- Analysis of the subsoil condition that can be used as the best alternative for the long term as a subsoil for an earthfill dam based on the amount of seepage discharge and the stability value of each soil.
- Analysis of the subsoil condition that can be used as the best alternative for the long term as a subsoil for an earthfill dam, regarding to seepage discharge value and the slope stability.
- Hydrological analysis to determine the 10-year return flood discharge value using HSS Nakayasu.

ANALYSIS AND DISCUSSIONS

In this study, two simulations are analyzed. The first simulation uses variations in the upstream water level elevation, which will be reviewed for each type of subsoil. The second simulation uses variations in several types of subsoil, which will be reviewed for each water level elevation.

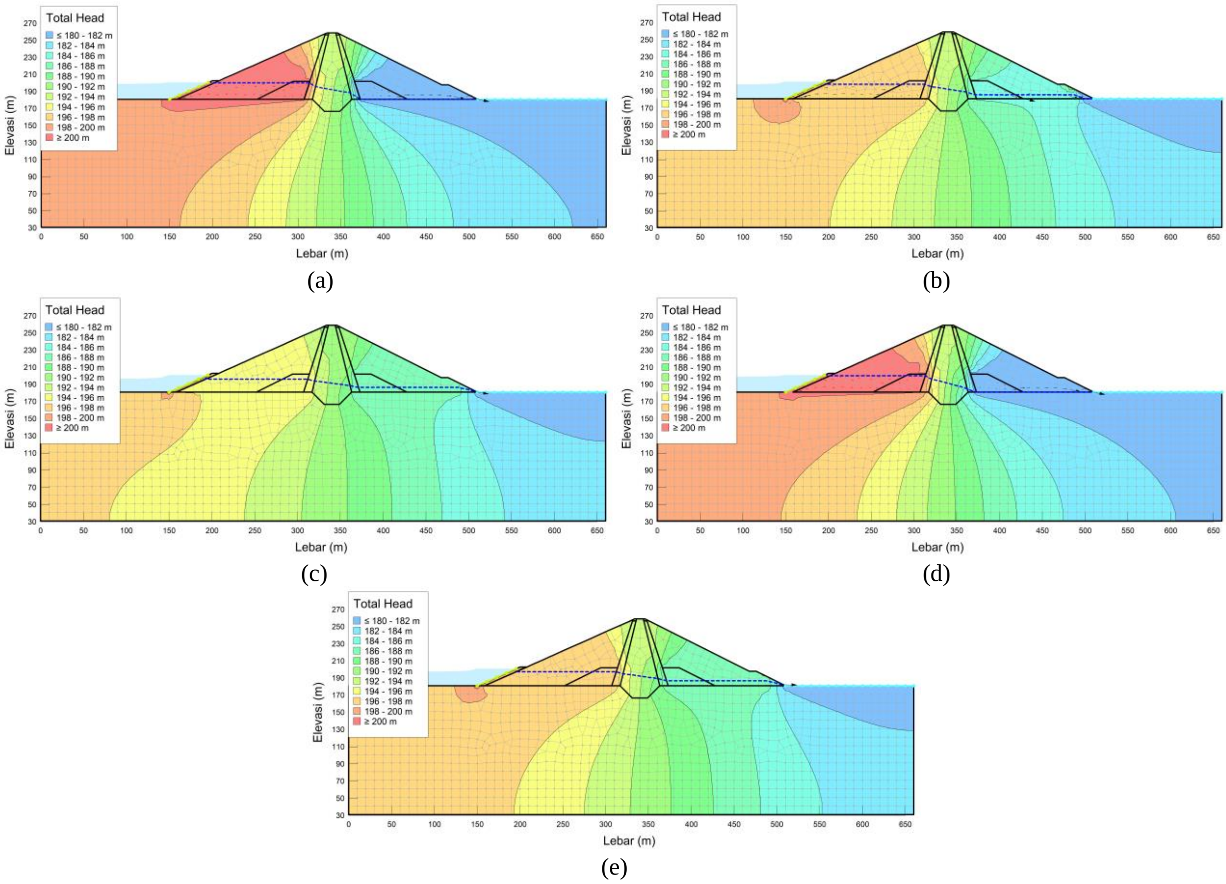

Figure 3 Total head contour for first simualation (a) clay; (b) silty clay; (c) silt; (d) silty sand; (e) sand

Prior to simulation, it is necessary to determine the boundary condition appropriately. The seepage analysis module aims to find seepage flow where it is the difference in hydraulic total head between two points or at a specific flow rate. In determining the seepage boundary condition, the input type is either H (Head) as the water level condition (measured from datum) or Q (discharge) as the flow of water through a field or channel. In this simulation, Head (H) is selected as the boundary condition. Meanwhile, the dam water level elevation is varied according to the simulation for the upstream section and the lowest elevation of the dam body for the downstream section.

A. FIRST SIMULATION

The results of the First Simulation test between 5 types of soil types with 15 water level conditions starting from 5 meters above the dam base elevation; +186 meter until +256 meter are shown in Figure 3. These five conditions indicate the flow of water which the total seepage discharge value is obtained from the dam body and dam subsoil according to Table 4.

More concisely, the Table 4 is illustrated by the graph in Figure 4. A logarithmic regression line is also obtained from the graph, which shows the relationship between water level elevation and the seepage discharge value that occurs.

Based on Figure 4, the logarithmic regression formula for each soil type is obtained as follows:

- Clay

$$y = 5.14\times10^{-6}\times\ln(x) - 2.70\times10^{-5} \qquad (1)$$

R^2 = 0,976; because it has an R^2 value of > 0,75 then the formula can be used

- Silty Clay

$$y = 3.69\times10^{-5}\times\ln(x) - 1.94\times10^{-4} \qquad (2)$$

R^2 = 0,956; because it has an R^2 value of > 0,75 then the formula can be used

- Silt

$$y = 1.10\times10^{-4}\times\ln(x) - 5.78\times10^{-4} \qquad (3)$$

R^2 = 0,987; because it has an R^2 value of > 0,75 then the formula can be used

- Silty Sand

$$y = 5.42\times10^{-4}\times\ln(x) - 2.83\times10^{-3} \qquad (4)$$

R^2 = 0,996; because it has an R^2 value of > 0,75 then the formula can be used

- Sand

$$y = 6.22\times10^{-3}\times\ln(x) - 3.26\times10^{-2} \qquad (5)$$

R^2 = 0,990; because it has an R^2 value of > 0,75 then the formula can be used

With:

y = Q = seepage discharge (m^3/s)

x = h = water level elevation (m)

Analysis type is couple numerical analysis by using seepage and slope stability analyses. The result of the stability simulation is the value of Safety Factors (SF), the SF value are variates and the tendency for clay soils to have the smallest value, between 1.310 to 1.366, sequentially, silty clay soils has values between 1.320 to 1.420 and silt soils has values between 1.360 to 1.525.

Table 3 Dams subsoil characteristics data

No	Soil Type	Seepage Code	Sat. VW_c (m^3/m^3)	Sat. K_x (m/s)	Note	
1.	Clay	C1	0.375	5.556 x 10^{-08}	M_v = 1.29 x 10^{-4} kPa γ = 16.00 kN/m^3	φ = 14° C = 40 kPa
		C2	0.380	1.230 x 10^{-08}		
		C3	0.690	2.900 x 10^{-09}		
2.	Silty Clay	SC1	0.360	5.556 x 10^{-07}	M_v = 1.00 x 10^{-4} kPa γ = 17.00 kN/m^3	φ = 18° C = 25 kPa
		SC2	0.430	1.944 x 10^{-07}		
		SC3	0.500	1.000 x 10^{-08}		
3.	Silt	Si1	0.390	2.889 x 10^{-06}	M_v = 2.00 x 10^{-5} kPa γ = 18.00 kN/m^3	φ = 22° C = 15 kPa
		Si2	0.460	6.944 x 10^{-07}		
		Si3	0.567	5.118 x 10^{-08}		
4.	Silty Sand	SS 1	0.380	1.228 x 10^{-05}	M_v = 1.33 x 10^{-5} kPa γ = 19.00 kN/m^3	φ = 34° C = 7 kPa
		SS 2	0.410	3.639 x 10^{-06}		
		SS3	0.458	1.000 x 10^{-07}		
5.	Sand	Sa 1	0.410	8.250 x 10^{-05}	M_v = 1.00 x 10^{-5} kPa γ = 20.00 kN/m^3	φ = 40° C = 40 kPa
		Sa 2	0.430	4.056 x 10^{-05}		
		Sa 3	0.470	1.000 x 10^{-05}		

Table 4 Seepage discharge for first simulation

Water Level Elev.	Seepage Discharge (m^3/s)				
	Clay	***Silty Clay***	***Silt***	***Silty Sand***	***Sand***
+186.00	1.37 x 10^{-08}	8.75 x 10^{-08}	2.88 x 10^{-07}	1.46 x 10^{-06}	1.61 x 10^{-05}
+191.00	1.47 x 10^{-09}	1.79 x 10^{-08}	6.41 x 10^{-07}	3.80 x 10^{-06}	3.67 x 10^{-05}
+196.00	1.70 x 10^{-07}	1.34 x 10^{-07}	4.37 x 10^{-06}	2.05 x 10^{-05}	2.21 x 10^{-04}
+201.00	2.44 x 10^{-07}	2.42 x 10^{-07}	3.22 x 10^{-06}	4.36 x 10^{-05}	3.27 x 10^{-04}
+206.00	3.53 x 10^{-07}	3.46 x 10^{-07}	1.10 x 10^{-05}	5.68 x 10^{-05}	6.30 x 10^{-04}
+211.00	4.33 x 10^{-07}	3.88 x 10^{-06}	1.32 x 10^{-05}	6.82 x 10^{-05}	7.56 x 10^{-04}
+216.00	5.40 x 10^{-07}	4.56 x 10^{-06}	1.55 x 10^{-05}	7.96 x 10^{-05}	8.82 x 10^{-04}
+221.00	6.47 x 10^{-07}	5.24 x 10^{-06}	1.77 x 10^{-05}	9.10 x 10^{-05}	1.01 x 10^{-03}
+226.00	8.09. x 10^{-07}	5.96 x 10^{-06}	1.84 x 10^{-05}	1.02 x 10^{-04}	1.13 x 10^{-03}
+231.00	8.97 x 10^{-07}	6.66 x 10^{-06}	2.22 x 10^{-05}	1.14 x 10^{-04}	1.26 x 10^{-03}
+236.00	1.05 x 10^{-06}	7.39 x 10^{-06}	2.45 x 10^{-05}	1.25 x 10^{-04}	1.28 x 10^{-03}
+241.00	1.15 x 10^{-06}	8.08 x 10^{-06}	2.68 x 10^{-05}	1.37 x 10^{-04}	1.51 x 10^{-03}
+246.00	1.33 x 10^{-06}	9.26 x 10^{-06}	2.90 x 10^{-05}	1.48 x 10^{-04}	1.70 x 10^{-03}
+251.00	1.44 x 10^{-06}	9.99 x 10^{-06}	3.18 x 10^{-05}	1.59 x 10^{-04}	1.90 x 10^{-03}
+256.00	1.68 x 10^{-06}	1.02 x 10^{-05}	3.41 x 10^{-05}	1.71 x 10^{-04}	1.89 x 10^{-03}

Meanwhile, silty sand and aand soils has the same value, 1.679; maybe the similarity of these values is influenced by the sand content, which tends to have similar internal friction angle value.

B. SECOND SIMULATION

The results of the Second Simulation test between 15 soil characteristics (from Table 3) with three water levels (from Table 2), which are flood water level, normal water level, and minimum water level, are shown in Figure 5.

A logarithmic regression line is also obtained from the graph, which shows the relationship between water level elevation and the amount of seepage discharge that occurs.

Based on Figure 5.a, in the condition of the flood water level, the logarithmic regression formula for each soil type is obtained as follows:

- Clay

$$Q = -4.21\times10^{-6}\times\ln(Sat.VW_c) - 5.56\times10^{-7} \quad (6)$$

R^2 = 0.787; because it has an R^2 value of > 0.75 then the formula can be used

- Silty Clay

$$Q = -4.21\times10^{-6}\times\ln(Sat.VW_c) - 5.56\times10^{-7} \quad (7)$$

R^2 = 0.990; because it has an R^2 value of > 0.75 then the formula can be used

- Silt

$$Q = -2.31\times10^{-4}\times\ln(Sat.VW_c) - 1.37\times10^{-4} \quad (8)$$

R^2 = 0.860; because it has an R^2 value of > 0.75 then the formula can be used

- Silty Sand

$$Q = -2.98\times10^{-3}\times\ln(Sat.VW_c) - 2.37\times10^{-3} \quad (9)$$

R^2 = 0.888; because it has an R^2 value of > 0.75 then the formula can be used

- Sand

$$Q = -2.38\times10^{-2}\times\ln(Sat.VW_c) - 1.77\times10^{-2} \quad (10)$$

R^2 = 0.993; because it has an R^2 value of > 0.75 then the formula can be used

With:

Q = seepage discharge (m^3/s)

Sat. VW_c = saturated volume water content (m^3/m^3)

Based on Figure 5.b, under normal water level conditions, the logarithmic regression formula for each soil type is obtained as follows:

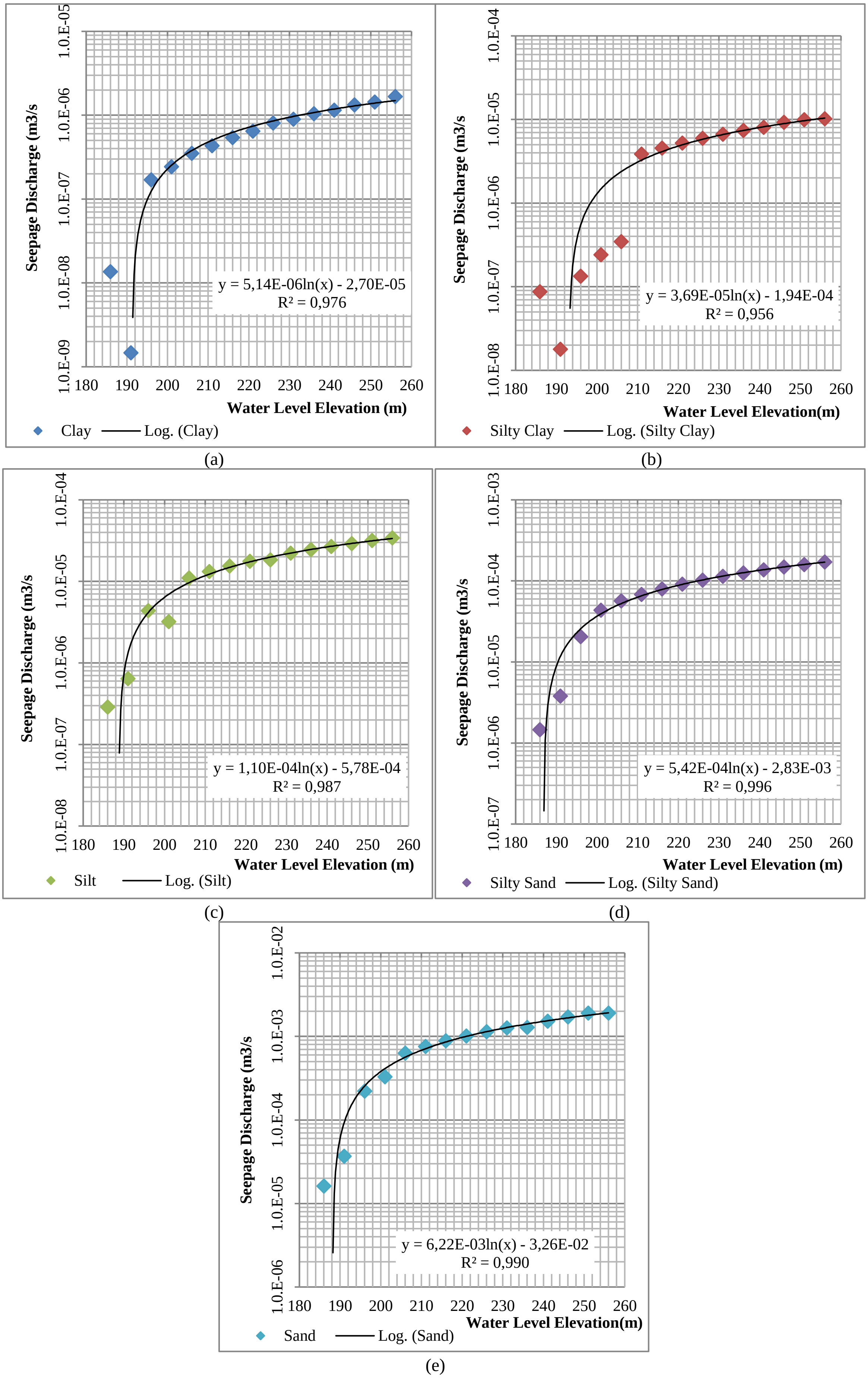

Figure 4 Graph of the effect of water level elevation on seepage discharge (a) clay; (b) silty clay; (c) silts; (d) silty sand; (e) sand

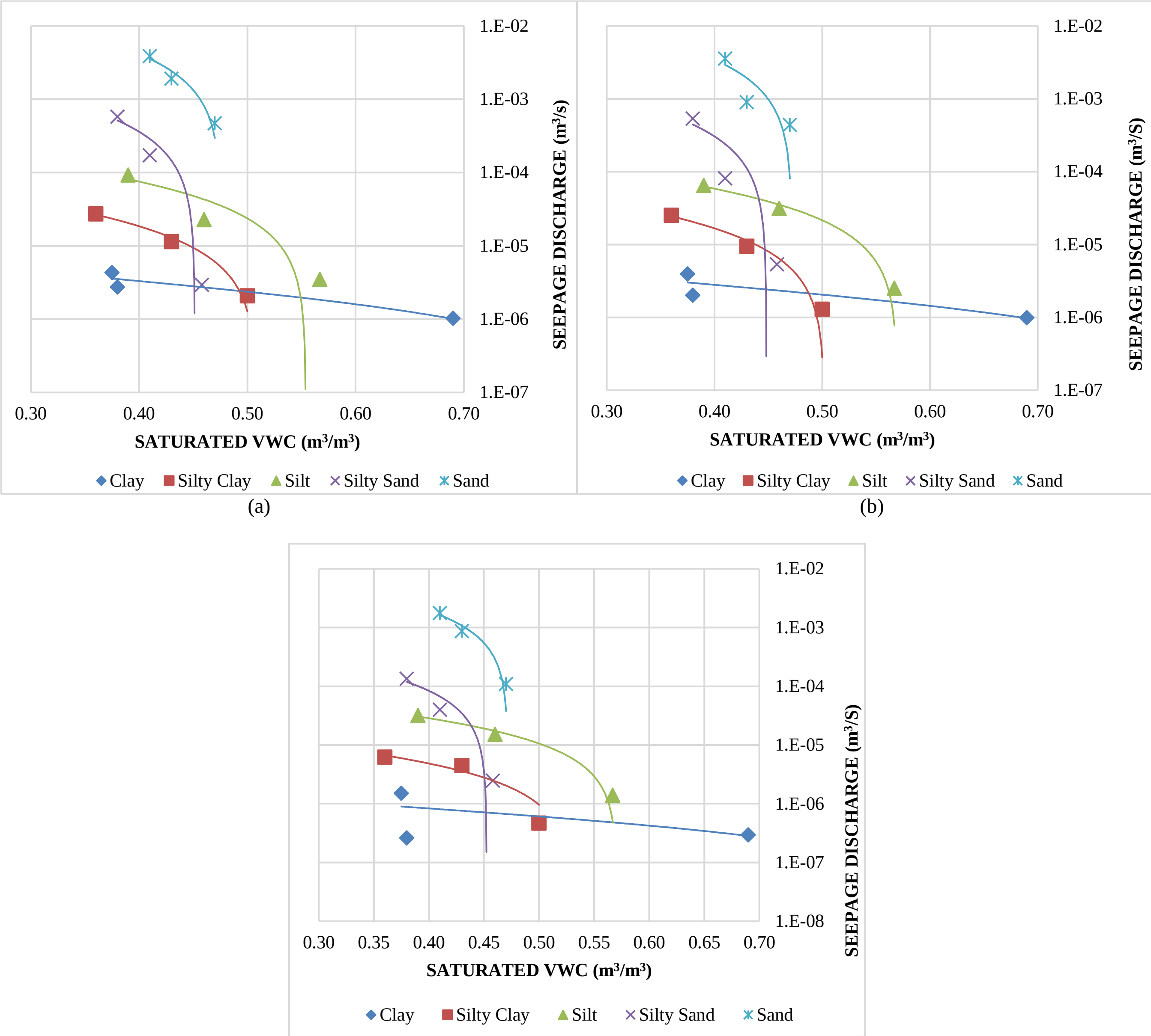

Figure 5 Graph of the effect of differences in saturated volumetric water content of each type of subsoil material for (a) flood water levels; (b) normal water level; (c) minimum water level

- Clay

$$Q = -3.35\times10^{-6} \times \ln(Sat.VW_c) - 2.72\times10^{-7} \quad (11)$$

R^2 = 0.600; because it has an R^2 value of < 0.75 then the formula cannot be used.

- Silty Clay

$$Q = -7.35\times10^{-5} \times \ln(Sat.VW_c) - 5.07\times10^{-5} \quad (12)$$

R^2 = 0.982; because it has an R^2 value of > 0.75 then the formula can be used.

- Silt

$$Q = -1.65\times10^{-4} \times \ln(Sat.VW_c) - 9.28\times10^{-5} \quad (13)$$

R^2 = 0.988; because it has an R^2 value of > 0.75 then the formula can be used.

- Silty Sand

$$Q = -2.68\times10^{-3} \times \ln(Sat.VW_c) - 2.16\times10^{-3} \quad (14)$$

R^2 = 0.772; because it has an R^2 value of > 0.75 then the formula can be used.

- Sand

$$Q = -2.07\times10^{-2} \times \ln(Sat.VW_c) - 1.56\times10^{-2} \quad (15)$$

R^2 = 0.719; because it has an R^2 value of > 0.75 then the formula can be used.

With:

Q = seepage discharge (m^3/s)

Sat. VW_c = saturated volume water content (m^3/m^3)

Based on Figure 5.c, at the minimum water level, the logarithmic regression formula for each soil type is obtained as follows:

- Clay

$$Q = -1.10\times10^{-6} \times \ln(Sat.VW_c) - 9.01\times10^{-8} \quad (16)$$

R^2 = 0.245; because it has an R^2 value of < 0.75 then the formula cannot be used.

- Silty Clay

$$Q = -1.74\times10^{-5} \times \ln(Sat.VW_c) - 1.11\times10^{-5} \quad (17)$$

R^2 = 0.930; because it has an R^2 value of > 0.75 then the formula can be used.

- Silt

$$Q = -8.06\times10^{-5} \times \ln(Sat.VW_c) - 4.53\times10^{-5} \quad (18)$$

R^2 = 0.986; because it has an R^2 value of > 0.75 then the formula can be used.

- Silty Sand

$$Q = -6.81\times10^{-4} \times \ln(Sat.VW_c) - 5.40\times10^{-4} \quad (19)$$

R^2 = 0.882; because it has an R^2 value of > 0.75 then the formula can be used.

- Sand

$$Q = -1.17\times10^{-2} \times \ln(Sat.VW_c) - 8.77\times10^{-3} \quad (20)$$

R^2 = 0.952; because it has an R^2 value of > 0,75 then the formula can be used.

With:

Q = seepage discharge (m^3/s)

Sat. VW_c = sat. vol. water content (m^3/m^3)

From the second simulation, the SF still have various value and the tendency for clay soils to have the smallest value, between 1.196 to 1.352, sequentially, silty clay soils has values between 1.371 to 1.401 and silt soils has values between 1.483 to 1.510. Meanwhile, silty sand and sand soils has the same value, 1.679; maybe the similarity of these values is influenced by the sand content, which tends to have similar internal friction angle value.

C. HYDROLOGY ANALYSIS

The hydrological analysis in this study used rainfall data from the Keser River watershed from the hydrological analysis in this study used rainfall data from the Sungai Keser watershed from two influential stations, which are Tugu Station and Pule Station, from 1995 to 2014. The planned rainfall was obtained from the Pearson Type III Log distribution of 129.258 mm. Furthermore, from this value, it can be calculated the amount of flood discharge with a return period of 10 years using the Nakayasu Synthetic Unit Hydrograph (HSS) the calculation is as follows [18][19]:

Flood discharge

t_g = 0.21 x $L^{0.7}$ = 0.21 x $9.295^{0.7}$ = 1.00

t_r = 0.75 x t_g = 0.75 x 1.00 = 0.75

T_p = t_g+0.8t_r = 1.00 + (0.8 x 0.75) = 1.60

$T_{0.3}$ = 0.47 $(A \text{ x } L)^{0.25}$ = 0.47 x $(43.06 \text{ x } 9.295)^{0.25}$
= 2.10

Q_{banjir} = (A x R_0) / {3.6(0.3 T_p + $T_{0.3}$}
= (43.06x129.258)/
{3.6x[(0.3x1.60)+ 2.10]}
= 598.74 m^3/s

From this value, according to the applicable regulations, the maximum allowable seepage discharge is 1% of the flood discharge, which is 5.987 m^3/s. It concludes that the seepage discharge that occurs in all types of soil is still allowed because it has a value below the maximum allowable seepage discharge.

CONCLUSIONS

From the simulation and analysis conducted in this study, it can be concluded as follows:

- Seepage on the subsoil of the dam occurs due to several factors, which are type of soil, saturated volumetric water content, and water level elevation.
- These factors have a logarithmic relationship with seepage discharge, the formulations obtained are different based on the type of soil used as subsoil. However, some formulas cannot be used because they have R^2 < 0.75. One of the formulations that can be used is for Silty Clay Soil is $y = 3{,}69 \times 10^{-5} \times \ln(x) - 1{,}94 \times 10^{-4}$; with y is for Seepage Discharge and x is for water level elevation.
- The most significant factor is the water level elevation; one example is from elevation +186 to +256 for silty clay, which has seepage discharge values ranging from 8.75 x 10^{-8} to 1.02 x 10^{-5} m^3/s. The seepage value range is below the maximum seepage discharge allowed by applicable regulations.
- The value of dam stability for Dam with all type of sub soil has a safety factor above 1.2. This value indicates that the soil on the dam is considered to be stable.
- Especially in the second simulation, some of the formulation results cannot be used because if R^2 < 0.75, these results may occure due to the lack of available data. So it is suggested to the researcher that it can be carried out directly in the laboratory to obtain more diverse and complete data.

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