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Piping Failure Remediation of Barrage Structure: from Analysis to Construction

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Abstract— Piping is the internal erosion under a dam/barrage structure because of seepage flow through the deposit of a granular soil layer. This phenomenon can cause a cavity under the barrage structure and trigger a collapse. Many water structures in Indonesia are made with simple structures so people can build them independently without heavy equipment; for example, the boulder barrage in Tinggar Buntut, Mojokerto. This barrage faced quite large piping. This study will present a detailed analysis and construction method for piping repair. Piping failure remediation of a barrage or other water structure required comprehensive approach including site observation, interview to the people in the nearest society, collect as built and historical data of the structure, conduct a good quality of soil investigation both in-situ and laboratory test, perform desk study and technical analysis, and good construction process and procedure. The piping analysis check can be done by using conventional methods like Lane's creep theory and numerical modelling like finite element by Plaxis software. Both methods give a good understanding regarding the piping mechanism and how to counter the potential piping failure. The best solution to increase factors of safety against piping is to add vertical wall. The construction method that can be utilized including strengthening the existing structure with concrete overlay and conduct grouting to the existence of crack or hole in the structure or surrounding supporting structure.

Keywords—barrage improvement; finite element method; lane theory; piping repair method

I. Introduction

Dam is one of the most important infrastructure that can provide a huge benefit for the surrounding community to boost the development of their environment [1]. A dam can provide many functions including water power plants, mitigation and control system of flood risk, stabilization of water flow speed [2], water supply, and recreation or tourism [3]. Dam usually classify according to the materials including earth dams which is constructed by compacting soil material and concrete dams which is made with concrete material [4]. Concrete dams fall into three categories: gravity, arch, and buttress dams, while earth dams are further divided into concrete faced-rock-filled dam (CFRD) and rock fill dams [4].

Tinggar Buntut dams collect water from Sadar River and transport it to the farming lands in surrounding areas. This water facility irrigates rice fields for ± 420 hectares in 6 villages with 720 farmers. This dam is in Tinggar Buntut Village, Bangsal sub-district, Mojokerto Regency, East Java Province. It was built independently by the local village community in 1992 by using river stone as the main materials. In 2019, the village community asked for government assistance to increase the capacity of irrigation discharge by adding a regulator gate on top of the dam's body, so that capacity increases and be able to irrigate more rice fields. The provincial government through the Brantas River Basin Center (BBWS) built 9 sluice gates along with electrical and mechanical devices, so that the status of the dams transforms from fixed dams to a movable dam with gates (Barrage) (see **Fig. 1**).

Recently, Tinggal Buntut Barrage is experiencing internal erosion which is causing the appearance of a hole in the downstream floor. This hole drains a large volume of water from the upstream side. A number of soil particles must be washed away as the water comes out. This erosion will lead to the barrage collapse as time goes by and will have domino effect to the sustainability of the rice field planting cycles.

Seepage under the dam body is a common problem that occurs in various dams in Indonesia. Many river dams built by the government or self-funded communities use stone masonry or reinforced concrete structures without prior careful planning. The condition of the soil beneath the dam structure was not identified in advance to review potential seepage problems that might occur.

Therefore, this research aims to investigate, analyze, and formulate the best construction method for pipping failure remediation with case study in the Tinggar Buntut Barrage, Mojokerto.

(a) (b)

Figure 1. (a) Front view and (b) back view of the Tinggar Buntut Barrage Mojokerto

II. LITERATURE REVIEW

Seepage problems have been analyzed and researched over the last few decades using various approaches, such as experimental, classical, mathematical analytical and numerical methods [5]. For the classical and mathematical analytical method are explained in detail by Garg in his book entitled Irrigation Engineering and Hydraulic Structure [6] including Bligh's creep theory for seepage flow, Lane's weighted creep theory, and Khosla Theory with the concept of flow nets. Meanwhile, for the numerical method for predicting the potential for piping in a dam can be done using the Distance Discriminant Analysis Model and Support Vector Machine (SVM) [7]. Apart from these two methods, evaluation of piping potential in dams/barrages can also be done using finite element method (FEM) programs such as Plaxis [8] [9].

Gao et al. [10] developed a solution procedure based on the use of a hybrid-finite element method to analyze steady-state linear seepage in two dimensions of an orthopic dam, where a hybrid function is used to connect interior elements and frame hydraulic head field elements. Abokwiek et al. [8] found that the width of the dam site is inversely proportional to the speed of seepage flow, where an increase in the width of 1 unit of dam site width will reduce the seepage rate by 3.7%. Furthermore, the depth of the dam base has an exponential inverse relationship to the seepage rate, where increasing the base depth of the dam structure can reduce the seepage rate by 73% at shallow depths and the effect decreases as the depth increases until it reaches a 1% reduction in the seepage rate. Meanwhile, the water level is linearly proportional to the seepage rate, where every 1 m increase in water level will increase the seepage rate by 10%.

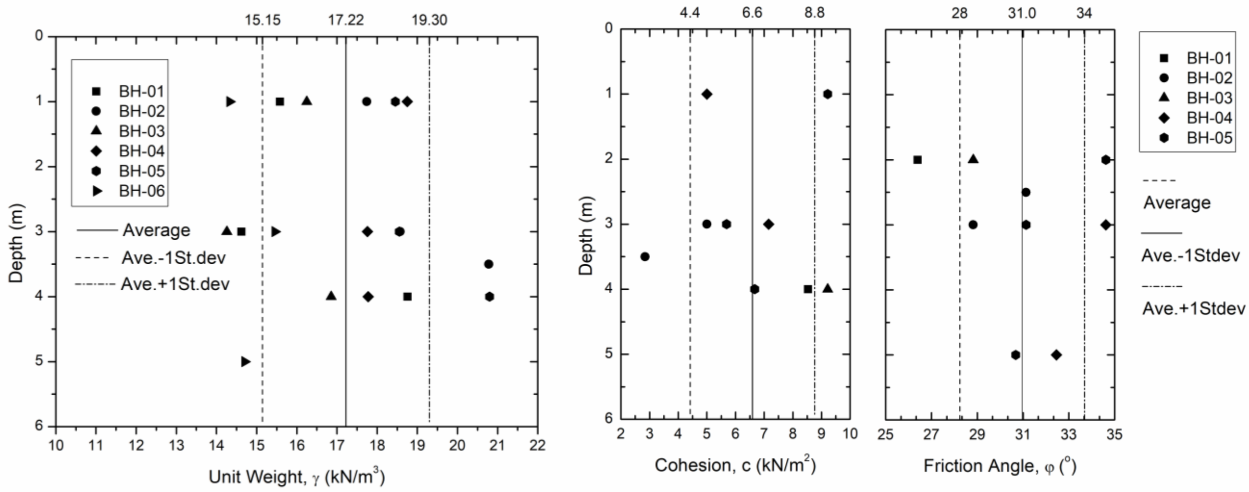
This research will utilize conventional method which is Lane's weighted creep theory and numerical method by using Plaxis software to conduct back analysis the phenomenon of the piping under Tinggar Buntut Barrage body and also evaluation the factor of safety the proposed repairing method toward piping failure.

III. MATERIALS AND METHODS

A. Soil Data

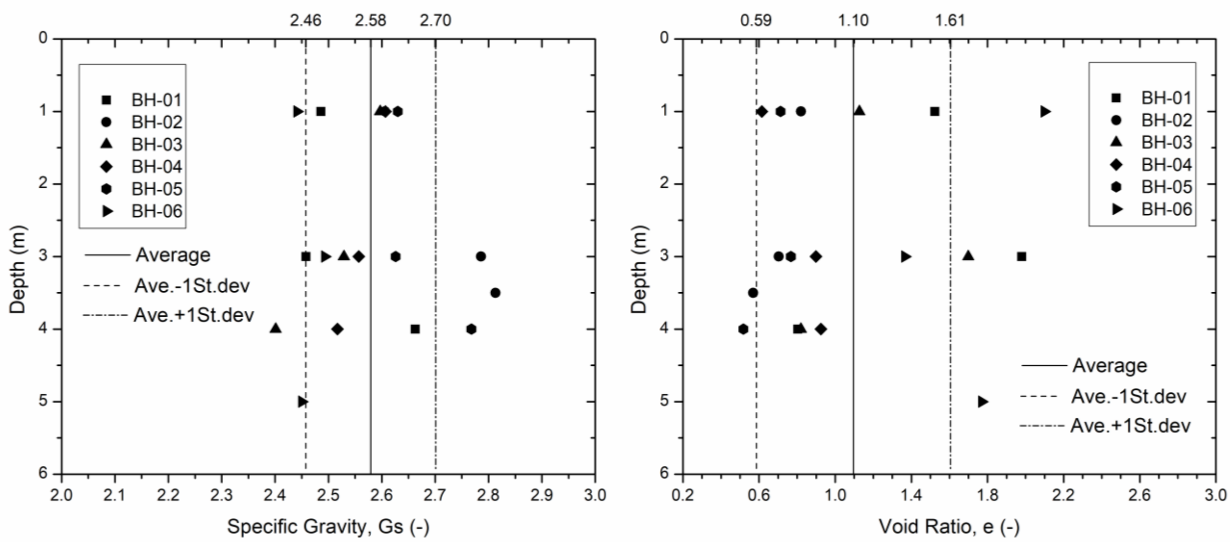
Soil investigation was conducted by in-situ dan laboratory testing for both undisturbed and disturbed soil samples which extracted during shallow boring. The in-situ testing was performed by hand boring test in the six locations which placed in upper stream and downstream of the barrage body (**Fig. 2**). On the other hand, complete laboratory testing was conducted including index properties (unit weight and specific gravity) and engineering properties (shear strength test, permeability test, dan consolidation test). The parameter versus depth is plotted in **Fig. 3** dan **Fig. 4**. It shows that all parameters value quite varies. The common practice usually utilizes simple statistical methods to select design parameters by calculating average value, average-1 standard deviation and average+1 standard deviation, where for conservative approach will choose average-1 standard deviation, but this research will take the average value. In the term of simplification, the soil along 5 meters depth will be assumed as homogeneous soil with the same parameter. The design parameters for unit weight, cohesion and internal friction are 17.22 kN/m^3, 6.6 kN/m^2 and 31^0, respectively (**Fig. 3**). While the design parameters for specific gravity and void ratio are 2.58 and 1.10, respectively (**Fig. 4**).The others parameters, which is needed to perform analysis in Plaxis software (**Table 1**), is synthesis by conducting correlation method with various references in the form graph or correlation tables as described in Look [11] and Carter & Bentley [12].

Figure 2. Layout of hand boringpoin around Tinggar Buntut Barrage



(a) (b)

Figure 3. Data distribution for (a) unit weight and (b) shear strength parameters



(a) (b)

Figure 4. Data distribution for (a) specific gravity and (b) void ration

Table 1. Soil parameters for analysis

No.	Type of soil	Model	Drainage	γ_{unsat}	γ_{sat}	E	ν	c'	φ'	Groudwater Flow		
				kN/m²	kN/m²	kN/m²	-	kN/m²	°	Classification	SWCC	Class
1	Sand	MC	Drained	18	18	20000	0.3	2	35	USDA	Van Genuchten	Sand
2	Silty Sand	MC	Drained	19	20	96000	0.3	10	37	USDA	Van Genuchten	Silty clay loam
3	Sand gain	MC	Drained	19	19	50000	0.3	10	40	USDA	Van Genuchten	Sand

B. Lane's Theory

Lane's theory is basically an improvement over Bligh's theory. Lane collected data from 200 dams all over the world and conducted analysis about the length of the creep. He found that the horizontal creep is less effective in causing loss of head than the vertical creep, so he proposed a weightage factor of 1/3 for the horizontal creep compared to 1.0 factor for vertical creep. **Fig. 5** shows the concept of creep length with the detailed equation as follows.

$$L_l = \left(d_1 + d_2\right) + \tfrac{1}{3}L_1 + \left(d_2 + d_2\right) + \tfrac{1}{3}L_2 + \left(d_3 + d_3\right) \quad (1)$$

$$L_l = \tfrac{1}{3}\left(L_1 + L_2\right) + 2\left(d_1 + d_2 + d_3\right) \quad (2)$$

$$L_l = \tfrac{1}{3}b + 2\left(d_1 + d_2 + d_3\right) \quad (3)$$

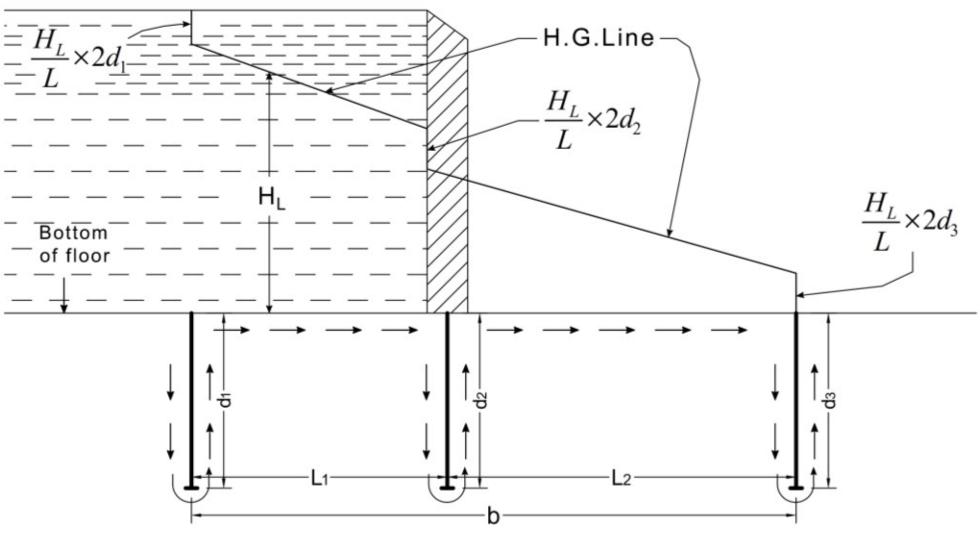


Figure 5. Creep length theory of the barrage or weir

The safety against piping is controlled by the following equation.

$$L_i > C_1 H_L \quad (4)$$

Where, H_L is the head causing flow as shown in **Fig. 5** and C_1 is Lane's creep coefficient as presented in **Table 2**.

Table 2. Value of Lane's coefficient for different types of soils

No.	Type of soil	Value of Lane's coefficient, C_1	Safe Lane's Hydraulic gradient should be less than
1	Very fine sand or silt	8.5	1/8.5
2	Fine sand	7.0	1/7
3	Coarse sand	5.0	1/5
4	Gravel and sand	3.5 to 3.0	1/3.5 to 1/3
5	Boulders, gravels and sand	2.5 to 3.0	1/2.5 to 1/3
6	Clayey soil	3.0 to 1.6	1/3 to 1/1.6

C. *Finite Element Analysis for Seepage*

There are some computer programs which developed based on finite element to tackle various geotechnical problems, such as Flac [13], Midas GTS NX [14], and Plaxis [15]. This research will utilize Plaxis program to conduct ground water flow under the barrage structure. A groundwater flow analysis consists of two types, which is a flow of water in saturated or in unsaturated soils. The common approach is assumed the soil as saturated. The flow of water in saturated soils is typically explained by Darcy's law (1856), which states that the flow rate is directly proportional to the gradient of hydraulic head [16]. Plaxis provides two types of ground water flow analysis, steady state and transient groundwater flow. Steady state is defined as a condition in which the hydraulic head and permeability coefficient at any point within the soil remain constant over time. This can be viewed as a scenario of groundwater flow as time approaches infinity. While the transient groundwater flow is defined as a condition in which the hydraulic head and permeability change with respect to time. This research will perform steady state analysis as the barrage has been built and operated for long time ago. The general equation is used inside the Plaxis for steady state analysis as follows.

$$\nabla^T \left[\frac{k_{rel}}{\rho_w g} \underline{\underline{k}}^{sat} \left(\nabla p_w + \rho_w \underline{g} \right) \right] = 0 \tag{5}$$

This equation shows that variation of pore water pressure with respect to time is zero or in another terminology can be said as the continuity condition applies. ∇^T is the gradient operator, k_{rel} is relative permeability which is defined as the ratio of the permeability at a given saturation to the permeability in saturated state, ρ_w is the water density, p_w is pore water pressure, g is gravitational acceleration, and $\underline{g}$ is the vector of gravitational acceleration which is defines as $\underline{g} = \left(0, -g, 0\right)^T$ and $\underline{\underline{k}}^{sat}$ is the saturated permeability matrix which is described in this following form. The detail equation and explanation can be found in the Galavi [16].

$$\underline{\underline{k}}^{sat} = \begin{vmatrix} k_x^{\ sat} & 0 & 0 \\ 0 & k_y^{\ sat} & 0 \\ 0 & 0 & k_z^{\ sat} \end{vmatrix} \tag{6}$$

Plaxis cannot calculate the factor of safety of a barrage or other water structure directly. Plaxis just analyze and visualize the groundwater flow which is in accordance with concept of flow net by Khosla's theory. The evaluation of piping failure potential is performed by calculating the exit hydraulic gradient (i_e) and critical hydraulic gradient (i_c). The output of gradient can be found inside the Plaxis by following this path: Plaxis Output – Stresses – Groundwater Flow – Hydraulic Gradient. The definition of factor of safety against piping failure follow the equation which is knows as Harza method [17]. The recommended value of SF against piping for dams is minimum 4 [17].

$$SF_{piping} = \frac{i_c}{i_e} \tag{7}$$

$$i_c = \frac{Gs - 1}{1 + e} \tag{8}$$

IV. Result and Discussion

A. *Back Analysis of Pipping Failure*

The sketch of initial condition and dimension of existing barrage structure is shown in **Fig. 6**. The back calculation by Lane's theory was conducted by follow the equation 1. The details calculations are as follows:

$$L_V = 0.3 + 2.0 + 1.0 + 0.2 = 3.5m$$

$$L_H = 5.5 + 2.0 + 3.0 + 20.0 = 30.5m$$

$$L_1 = L_v + \tfrac{1}{3} L_H = 3.5 + \tfrac{1}{3} 30.5 = 13.67m$$

The soil under barrage identified as sand with medium size, so the C_1 value is taken as interpolation between fine sand (C_1=7) and coarse sand (C_1=5), which is equal to C_1=6. The head causing water flow is 4 m as shown in **Fig. 6**.

$$C_1 H_L = 6 \times 4 = 24m$$

Because the value of $C_1 H_L$ still greather than the value of L_1, so that there will be a piping and in further will lead to the collapse of the Tinggar Barrage.

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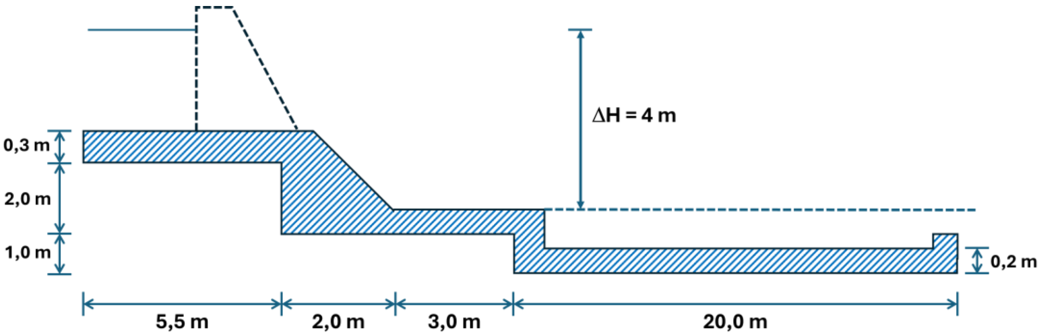

Figure 6. Initial dimension of barrage structure

While the back analysis with numerical method by using Plaxis software was performed with detailed geometry as shown in **Fig. 7**. The first layer (yellow color) is sand soil, and the second layer (green color) is silty sand soil, while for the soil under barrage structure (orange color) is sand gain soil which is stronger sand soil due to the consolidation process along the period since the barrage was built. The detailed soil parameter input is presented in **Table 1**. The barrage structure (brown color) is modelled as linier elastic material with non-porous drainage type, γ 20 kN/m^3, E 200000 kN/m^2, and ν 0.2. The water level (head in the upstream side) is modelling with phreatic line as shown in the **Fig. 6** so that the difference with the water level in the downstream side is equal to 4 m.

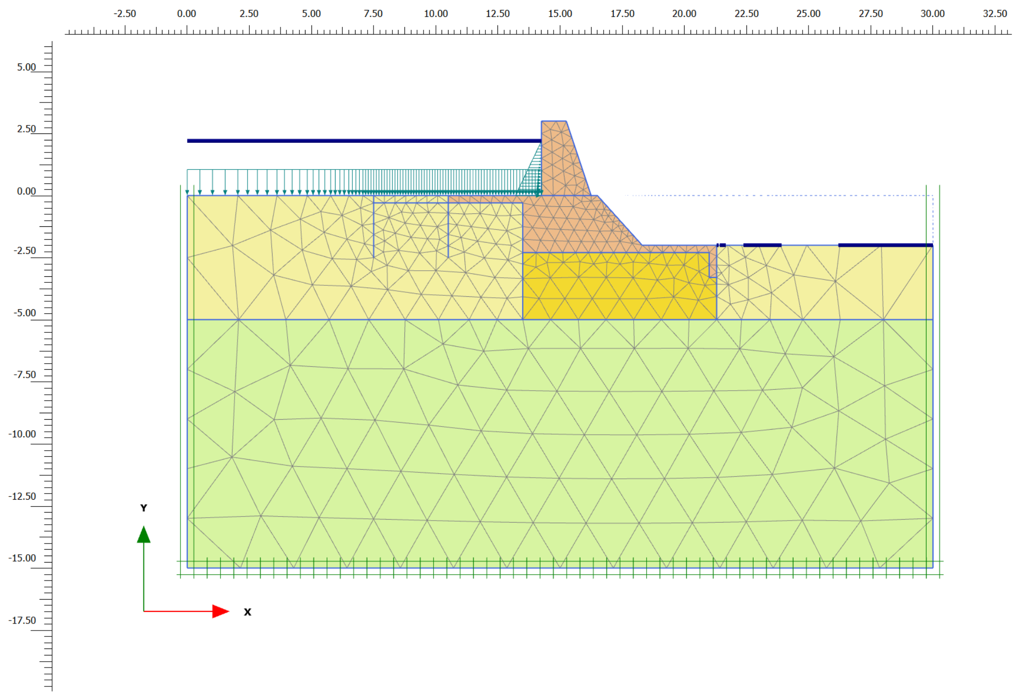

Figure 7. Model geometri of existing barrage for back analysis using Plaxis

The groundwater flow is performed by using steady state analysis. The visualization of hydraulic gradient shown in **Fig. 7** including color scale which shows the magnitude of the hydraulic gradient value along the soil cluster. From the color scale, it can be identified that the maximum hydraulic gradient at downstream side (exit gradient) is between 0.30 to 0.40. The value of critical gradient is calculated by following equation 8 and the parameter of G_s and e can be extracted from **Fig. 4**. After that, the factor of safety against piping can be calculated, and the result is 1.875 which is less than minimum criteria (SF$_{min}$ = 4), so that it is confirmed that the piping failure of the barrage was caused by the structure not sufficient.

$$i_c = \frac{Gs-1}{1+e} = \frac{2.58-1}{1+1.10} = 0.75$$

$$SF_{piping} = \frac{i_c}{i_e} = \frac{0.75}{0.40} = 1.875$$

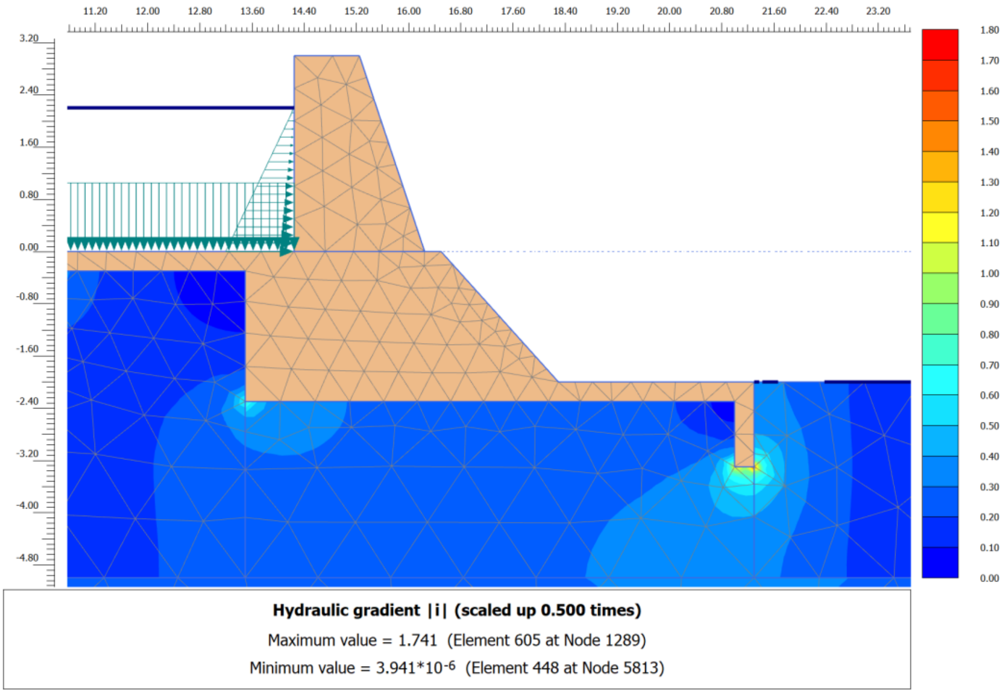

Figure 8. Plaxis output – hydraulic gradient of the existing barrage

B. Design Calculation of Piping Remediation

The back analysis by using Lane's theory give result that the value of L_1 need to be 10 m greater to fulfill the criteria at not less than the value of C_1H_L = 24 m. The best way to achieve 10 m is adding vertical walls in the upstream side, so that the proposed design is adding 2 rows of vertical wall with height 2.5 m and spacing 3 m (**Fig. 9**). The update calculation shows that the new value of L_1 is 24.67 which is greater than C_1H_L, so that the design is sufficient against piping.

$$L_v = 3.5m + 2(2.5 + 2.5) = 13.5m$$

$$L_H = 30.5 + 3 = 33.5m$$

$$L_1 = L_v + \tfrac{1}{3}L_H = 13.5 + \tfrac{1}{3}33.5 = 24.67m$$

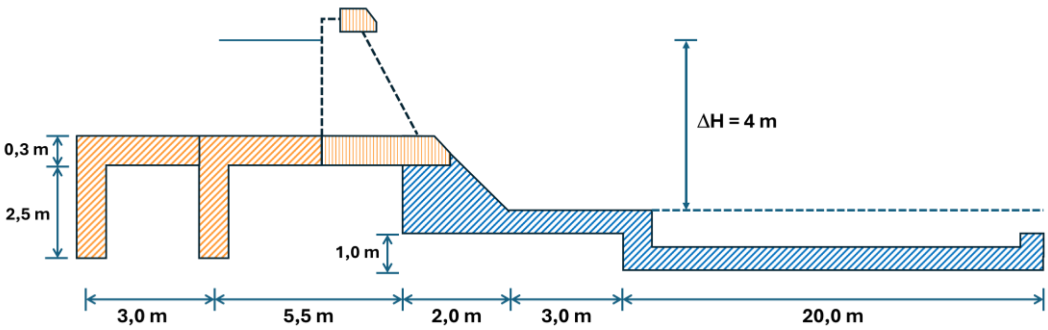

Figure 9. The proposed design for piping failure remediation

Meanwhile, the Plaxis model is also updated by adding 2 lines of vertical wall which is modelled by using plate element. The shading visualization of hydraulic gradient (Fig. 10a) shows that the value slightly decreases to around 0.20 to 0.30 compared to the existing hydraulic gradient was 0.40 (which is 0.1 to 0.2 smaller). The cross section of hydraulic gradient in the downstream area was made to get precise value (Fig. 10b) which is 0.238. Therefore, the factor of safety increases to 3.15. Even though this SF value still less than minimum criteria (SF_{min} = 4), but the value is quiet high and can be consider as the safe value against potential of piping failure.

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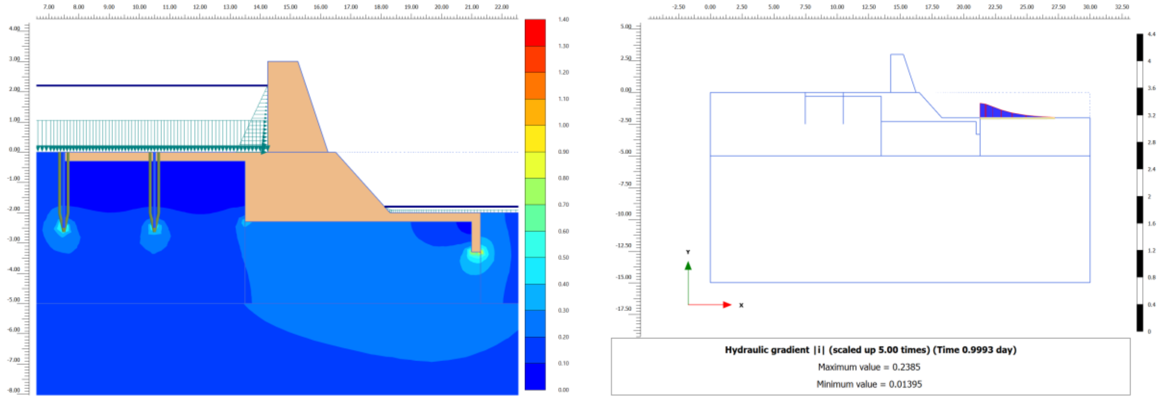
$$SF_{piping} = \frac{i_c}{i_e} = \frac{0.75}{0.238} = 3.15$$



(a) (b)

Figure 10. Plaxis result of proposed design (a) shading visualization of hydraulic gradient and (b) cross section of hydraulic gradient in the downstream

C. Construction of Tinggal Buntut Barrage Strengthening

The upstream floor is strengthened by K-400 quality concrete with a dimensions 33 meters wide, 8.5 meters long (including the extension of the floor) and 25 cm thick (**Fig. 11a**). Additional beams between the pier is also constructed to increase stiffness and unity among the piers. The reinforcement on the floor used M8 wire mesh, while the reinforcement on the beam used 6 pieces of D19 steel bar. The main items are additional two rows of cut of wall with height 2.50 m in each. This barrier wall material is precast flat concrete sheetpile (**Fig. 11b**).

(a) (b)

Figure 11. (a) construction of upstream floor strengthening and (b) installation of barrier wall

(a) (b)

Figure 12. (a) construction of downstream floor strengthening and (b) beam strengthening

The downstream floor is also strengthened by K-400 quality concrete with a dimension 33 meters wide, 2.5 meters long and 20 cm thick (**Fig. 12a**). The beam in the upper side of the pier which is functioning as crossing path for people and also motorbike is strengthened with additional reinforcement and concrete to increase the stiffness connection between the piers (**Fig. 12b**). The reinforcement on the floor used M8 wire mesh, while the reinforcement on the beam used 6 pieces of D19 steel bar.

The piping failure of the existing barrage structure causing some holes in the floor and stone masonry of slope facing in the left and right side of the structure (**Fig. 13**). The normal concrete mix is not suitable to make sure all the crack path fulfill by the admixture, so that the grouting method with special grouting cement was conducted.

(a)

(b)

Figure 13. (a) grouting process of the stone masonry wall and (b) grouting process of the floor

V. Conclusion

Piping failure remediation of a barrage or other water structure required comprehensive approach including site observation, interview to the people in the nearest society, collect as built and historical data of the structure, conduct a good quality of soil investigation both in-situ and laboratory test, perform desk study and technical analysis, and good construction process and procedure. The piping analysis check can be done by using conventional methods like Lane's creep theory and numerical modelling like finite element by Plaxis software. Both methods give a good understanding regarding the piping mechanism and how to counter the potential piping failure. The best solution to increase factors of safety against piping is to add vertical wall. The construction method that can be utilized including strengthening the existing structure with concrete overlay and conduct grouting to the existence of crack or hole in the structure or surrounding supporting structure.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Danang Setiya Raharja contributed to perform analysis of piping using finite element modelling and wrote the articles for around 70 percent. Soebagio contributes to constructing the piping remediation method including supporting the real condition during construction. Siswoyo contributes to supply and analysis the soil data either in-situ or laboratory test.

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