The importance of investing in site characterization in a dam project to avoid impending losses

Andhika Sahadewa
Civil Engineering, Institut Teknologi Bandung, Bandung, Indonesia, sahadewa@ftsl.itb.ac.id

Haris E. Setyawan[1], Mahdi I. Tanjung[2]
Research center for water resources, Ministry of Public Works & Housing, Bandung, Indonesia, kingharist@gmail.com[1], mahdi.ibrahim7@gmail.com[2]

Aprianto D. Indrawan, Ridwan B. Santoso
Wijaya Karya, Jakarta, Indonesia

Ratika N. Salim
Civil Engineering, Institut Teknologi Bandung, Bandung, Indonesia

Abi M. Hakim
Civil Engineering, Institut Teknologi Indonesia, South Tangerang, Indonesia

ABSTRACT: In dam design, site characterization, aside of providing engineering property values, should be able to capture the variability and complexity of geotechnical, engineering geology, hydrogeology conditions in the dam sites. This information plays critical role as it frequently becomes a basis in selecting different scenarios in the design. This paper presents a case study of a rockfill dam construction in Indonesia highlighting the importance of site characterization in reducing uncertainties. In the early construction stage, additional field investigation was performed and identified the presence of high-porosity confined aquifer layer below dam foundation. This finding urged that the initial design of grouting curtain wall could no longer be applied. Dam redesigning required considerable effort and resulted in time and financial losses. Investing in site characterization is believed to reduce uncertainties that eventually avoiding any imminent negative consequences.

Keywords: rockfill dam design; grout curtain; secant pile; site characterization

1. Introduction

Site characterization is one of the main important stages in dam construction. Frequently, its results guide type selections of dam, foundation, drainage curtain etc. Unfortunately, many still underestimate the importance of site characterization for dam design and allocate limited resources. This paper presents a case study of a rockfill dam construction in Indonesia highlighting the importance of site characterization, where putting aside more investigation in the early stage has imposed great consequences in the following stages, including the selection of seepage-reduction method.

Seepage-reduction or water barrier is one of crucial considerations for increasing dam stability. Available seepage-reduction methods include impermeable cut-offs, grout curtains, and upstream blankets. Seepage-reduction system reduces energy of high water pressure and seepage forces at the base of dam leading to water pressure and seepage forces without adverse effects in the downstream region. In addition, these seepage-reduction methods are also used to:

- Reduce the permeability of foundation below the dam
- Increase the seepage length of equipotential flow line
- Reduce the likelihood of piping through open joints in the dam foundation
- Improve the efficiency of the foundation drains
- Support dam function as a water storage

It should be noted that the seepage-reduction method should be complemented with properly designed filters and drainage features. During the 1st Rankine lecture, Casagrande went onto to assert that grout curtains may not have a significant influence on the seepage conditions, i.e. they cannot be implicitly trusted to eliminate seepage flow beneath or around a dam [1].

The M Dam, 60-m tall, presented in this article is located in Sulawesi and is designed to have an impermeable upright core. Having capacity as large as 23.37 m^3, this dam is designed to reduce flood debit of 282 m^3/s. In addition, the dam can supply 4.50 m^3/s water and 1.20 MW electric energy. Regionally, M Dam is situated in quarterly young volcanic product that has not undergone a complete cementation process, such as sandy tuff, clay, and lapilli tuff. These materials are poor, easily errored by water, and easily broken by impact load.

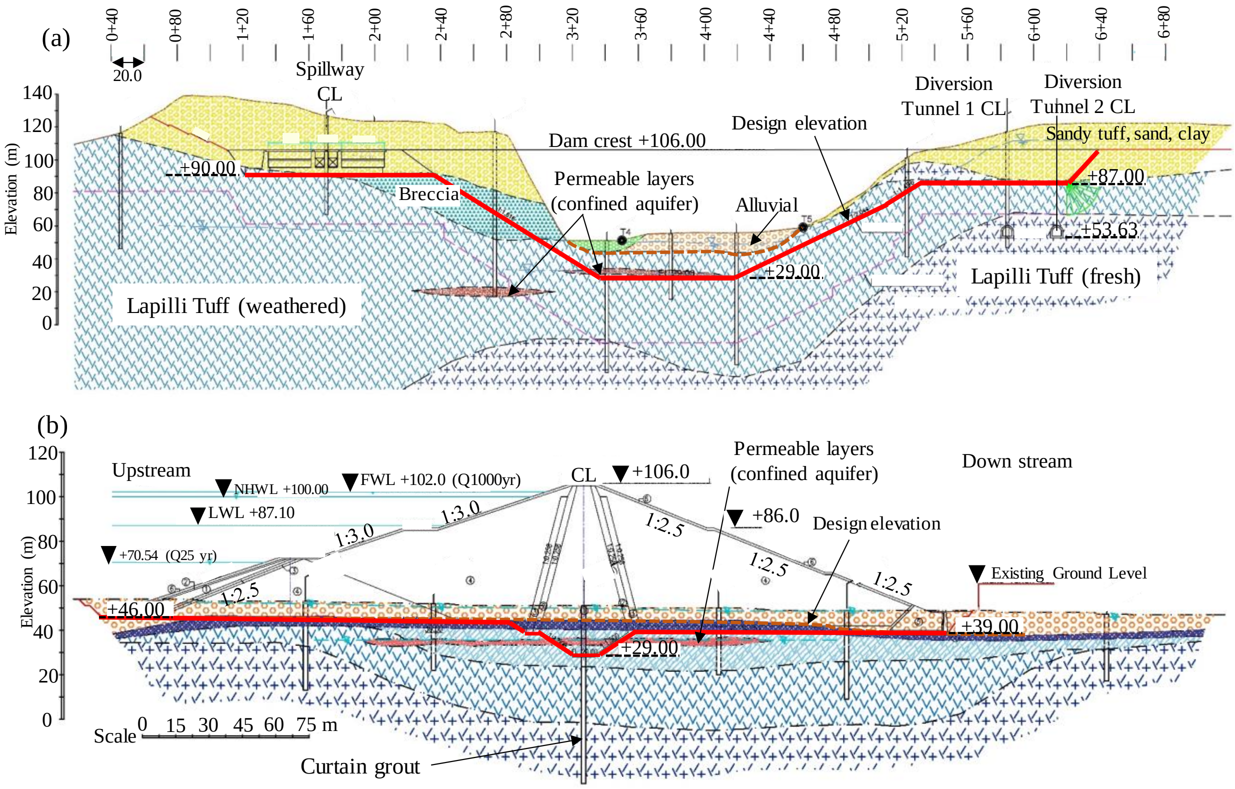

Figure 1. Dam design prior to additional site characterization: (a) long section and (b) cross section

2. Initial interpreted site characteristics and dam design

The interpreted soil-rock stratigraphy and the design of M Dam prior to additional site characterization are presented in Fig. 1. As shown in this figure, dam base is constructed by excavating alluvial, breccia, weathered lapilli tuff layers from elevation of +90.00 m to +29.00 m. This design is based on consideration that better lapilli tuff is estimated to be found at el. +29.00 m. In addition, excavation up to this elevation ensures the removal of water-bearing permeable layer. The presence of this water-bearing permeable layer was realized in the initial site investigation. After performing standard penetration test measurement, water with head height of 2.07 m bursting out from a Ø73 mm drill casing. Seven other drilling points also experienced the same water bursting with head height varied from 1.2 m to 1.72 m. The presence of artesian water that had head higher than water table of the river suggesting that this water-bearing permeable layer was a confined aquifer. This layer was estimated about 10 m to 15 m thick at el. +32.00 m, which is top elevation of sandy tuff, and inter with lapilli tuff and sandstone as thick as 1 m to 2 m at el. +49.00 m.

Grout curtain as long as 40 m was selected as the seepage-reduction method for this dam. This curtain was designed to be capped with 1-m thick concrete cap and completed with a pair of 10-m long grout sub-curtains located 2-m in the behind and in the front of the curtain.

Trial grouting test is commonly performed to evaluate the amount and mixture of grout as well as hydraulic conductivity of the ground in term of lugeon value. This test is also important to evaluate whether the ground is safe under the applied grouting pressure. In general, this test consists of drilling a hole up to certain depth, performing lugeon test (packer test), and injecting grout. This cycle is performed until the required depth is reached. At least, 3 boreholes in a triangular pattern with certain spacing are needed. A check hole at the center of the triangle is drilled up to borehole depth or 5 m deeper. This check hole is used to perform Lugeon test. Thus, the lugeon values before and after grouting can be compared to evaluate grouting effectivity.

In this project, trial grouting test was performed prior to grout curtain installation along dam as, in location T1, T2, and T3 (Fig. 2). Trial tests in T1 and T2 were conducted up to depth of 40 m. The trial borehole spacing for T1 and T2 are 3 m and 2 m, respectively. Testing in T3 was conducted up to depth of 20 m with borehole spacing of 1 m. Test result in T1 indicated a mediocre grouting effectivity, with average value of 45.98%. In T2, the trial result also indicated a mediocre grouting effectivity as well. Nevertheless, high grouting effectivity was shown at depth of 20 – 25 m having a very Lugeon value of 0.43. Trial test in T3 showed good grouting effectivity with significantly lower Lugeon value. Nevertheless, coring using phenolphthalein 0.1n did not show grout cement trace. In T3 location, 2 other boreholes were made to form a 0.3 m-spacing triangular pattern with an initial borehole. For this spacing, grouting effectivity reached > 80%. A 0.1n phenolphthalein test on the core also showed the presence of grout cement (Fig. 3).

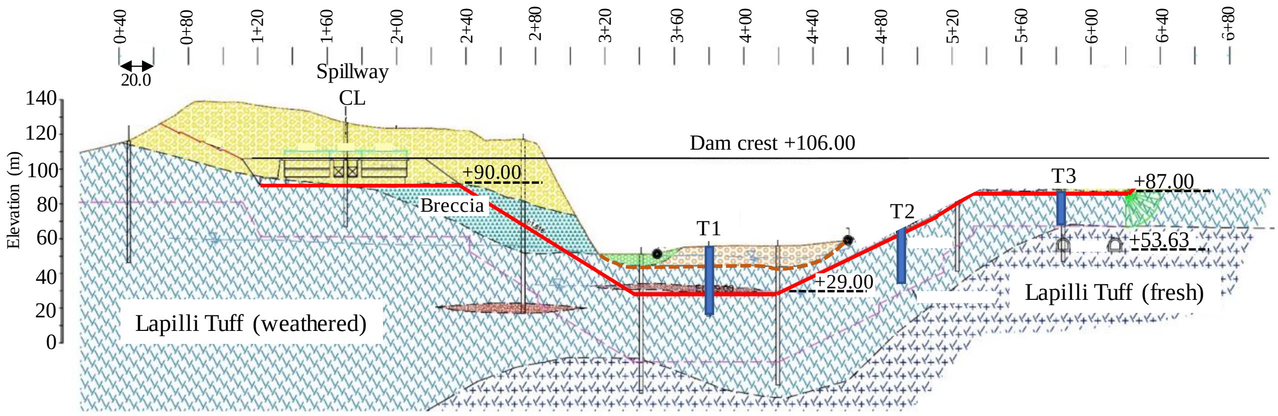

Figure 2. Locations of trial grout testing

Figure 3. Phenolphthalein traces

The result of grout trial test discouraged the use of grout curtain in M Dam. It was considered in this project that use of grout may not be able to provide reliable performance in the seepage-reduction system. In addition, grout treatment spacing of 0.3 m was a way much more expensive than the design treatment spacing of 2.4 m. Based on this reason, the use of grout curtain was under further evaluation.

3. Additional soil investigation

To find the optimum solution for seepage-reduction method in M Dam, a series of additional site investigation was performed. This site characterization included full core drilling in 5 locations along the main dam axis and 2 deep drillings up to 80 m to evaluate the continuity and permeability of water bearing layer. Considering the presence of loose material leading to difficulty in obtaining undisturbed sample for laboratory testing, in-situ testing was proposed. This in-situ evaluation consisted of pressuremeter/lateral load test and seismic downhole test.

3.1. Pressuremeter test

Pressuremeter test in this project was used to assess Young modulus (E) values of the material. The E value then can be used to categorize the material. For example, The Central Research Institute of Electric Power Industry (CRIEPI) rock mass classification can be applied to hard rock, such as igneous rocks and soft consolidated sedimentary rocks [2]. This classification can be adopted for dam foundation, tunnel, and quarry. Based on combined data of rock weathering stages, joint, crack, rock can be classified into 6 classes, namely A, B, CH, CM, CL, and D as shown in Table 1. At depth of 10 m to 15 m, pressuremeter test showed that Young's modulus values ranging from of 81 N/mm^2 to 603 N/mm^2. According to CRIEPI, material with this E value range categorized as strongly weathered (D class). The highest E value, which was 681 N/mm^2, even still can be considered as D class rock. Readers are referred to Saito [2] for more detail description of CRIEPI rock mass classification.

At depth of 27 m to 28 m, pressuremeter test results showed the presence of low E values ranging from 2.7 N/mm^2 to 80 N/mm^2. This layer was interpreted as sandy material located in the confined aquifer and consistent with full core drilling result.

The interpreted E values suggested that sound well-cemented tuff layers may not be observed at shallower depths. Even at depth of 30 m below riverbed, sound rock material still was not found. Thus, excavation for dam foundation up to el +29.00 m was not needed any longer. Excavation to el. +39.00 m was then proposed to remove alluvial material.

Table 1. CRIEPI Rock Classification [2]

Class	Modulus of Deformation (kg/cm^2)	Modulus of Elasticity (kg/cm^2)	Shear Stress		Seismic Velocity (km/sec)	Unconfined Compressive Strength q_u (kg/cm^2)
			Cohesion (kg/cm^2)	Internal Friction Angle (°)		
CH	20,000	60,000	20	45	2.5	CH
CM	8,000	24,000	10	35	1.8	CM
CL	4,000	12,000	8	30	1.5	CL
D	2,000	6,000	5	28	1.2	D

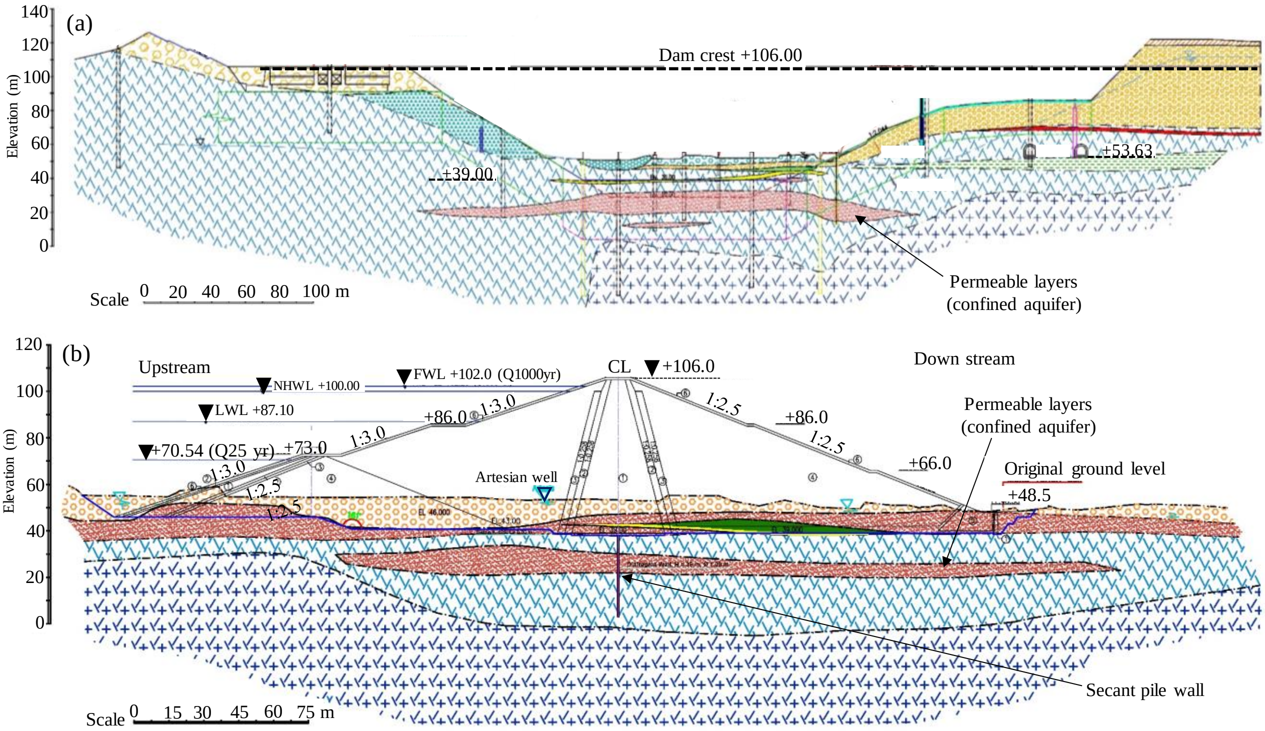

Figure 4. Dam design after additional site characterization: (a) long section and (b) cross section

3.2. Seismic downhole test

Seismic downhole test was carried out to measure primary wave velocity (V_p). Field test showed that V_p in this project location ranging from 459 m/s to 712 m/s. According to Bell [3], rock up to testing depth in this site can be categorized as very soft rock hardness (Table 2). Seismic downhole test results were consistent with pressuremeter test results.

Table 2. Rock class and seismic velocity [3]

Rock Hardness Description	Unconfined compressive stregth (Mpa)	Seismic wave velocity (m/s)	Spacing of Joints (mm)
Very Soft	1.7 - 3.0	450 - 1200	<50
Soft	3.0 - 10	1200 - 1500	50 - 300
Hard	10 - 20	1500 - 1850	300 - 1000
Very Hard	20 - 70	1850 - 2150	1000 - 3000
Extremely Hard	>70	>2150	>3000

3.3. Dam redesign consideration

The additional site characterization concluded that there was no sound rock nor well cemented rock at el. +29.00 m or even at much greater depth. In addition, the confined aquifer layer was found to be much greater than initially expected (Figure 4). Initially, it was planned to remove this permeable layer (confined aquifer) and founded the dam at sound or well cemented rock. After additional site characterization, it was proposed that dam foundation excavation would be only performed up to el. +39.00 m. This consideration was also based on workability reason, such as difficulty in excavating river trench and dewatering up to el. +29.00 m.

Rockfill in general could be founded on soil or soft rock as long as bearing capacity and deformation fulfill the requirements. As the foundation of M Dam still in weathered tuff, bearing capacity and deformation were recalculated using the new parameter from the additional site characterization. According to Indonesian Rockfill Design Guide [4], foundation rock generally will not have issue in bearing capacity. Nevertheless, it is seepage issue that needs to be considered as it can lead to erosion. In addition, seepage can result in water-loss from dam through joint, fissures, and crevices, permeable layers, along fault plane or other places. In order to mitigate this issue, cement injection or cut-off wall using plastic cement can be used. In addition, foundation settlement due to main dam fill needs to be evaluated. Stability of dam body also has to be rechecked. If it is not satisfied, counterweight in upstream and downstream need to be constructed.

It was confirmed that some locations are dominated by poor cemented sandstone or granular soil. Thus, liquefaction analysis was performed to evaluate liquefaction-related stability on dam foundation during a seismic event.

Dam redesigning required considerable effort and resulted in time and financial losses. Contractor had to stand by on site waiting for the new design. Recertification progress on the new design also consumed significant duration. If in the early stage considerable resource has been budgeted for better site characterization, including mapping the presence of confined aquifer layer, identification of weathered tuff quality, proper selection of seepage-reduction system would have been

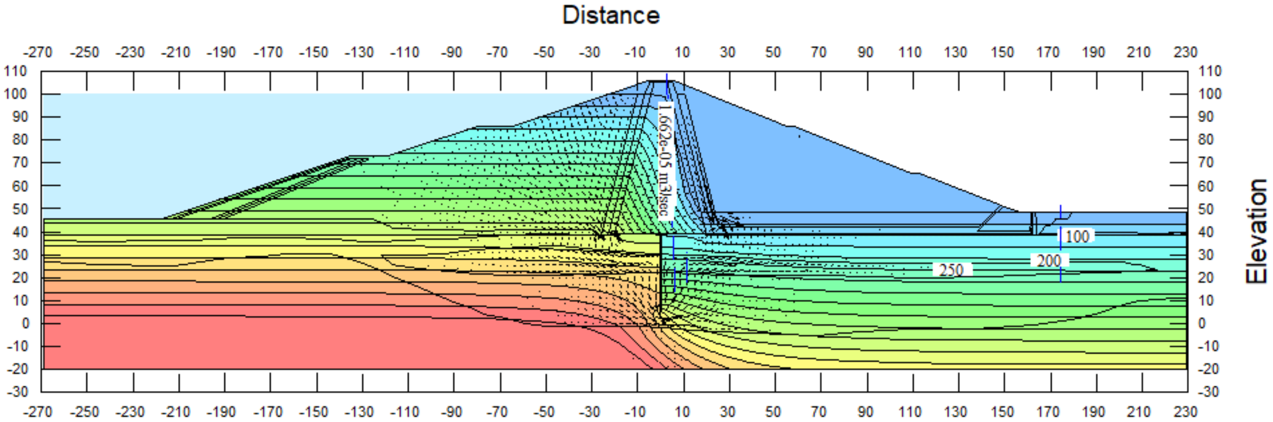

Figure 5. Example of seepage analysis in M Dam

proposed since the beginning. Investing in site characterization is believed to reduce uncertainties that eventually avoiding any imminent negative consequences.

4. Secant pile as cut-off wall

Cut-off wall is one of seepage-reduction methods that can be used when grout curtain is no longer economic. For rockfill dam, the following cut-off wall can be made of:

- Conventional concrete
- Slurry bentonite cement
- Plastic concrete

In M Dam, it was eventually decided to use secant pile as the cut-off wall. Though grout curtain is more frequently used as seepage-reduction system in Indonesia, secant pile is gaining popularity. Examples of successful secant pile use as water barrier can be found in Arapuni Dam, New Zealand [5], Folsom Dam, United States [6], and Beaver Dam, United States [7]. Readers are referred to Newman et al [6] for design and construction of a secant-pile wall in variable ground conditions in dam. Secant pile has also been constructed under water up to 30 m deep, such as reported in Walter F. George Dam [8].

The design of secant pile consists of a series of 35-m long bored piles having diameter of 3-m installed with 30 cm overlap. The use secant pile in M Dam also overcomes the issue of confined aquifer below dam foundation. To complement this water barrier system, relief well in the downstream toe is proposed.

5. Evaluation of revised dam design

Revised dam design needed to be evaluated to justify design change in foundation excavation elevation and seepage-reduction method from grout curtain to secant pile. Mainly, these changes are attributed to the presence of permeable layer in dam foundation leading to difficulty in grouting installation. Evaluation of revised dam design has been conducted by design team, including:

- Conventional concrete
- Slurry bentonite cement
- Seepage analysis in steady state condition
- Seepage analysis in transient condition
- Deformation analysis due dam construction
- Seismic analysis: dam stability and liquefaction analysis

Some of them are presented in the following parts.

5.1. Seepage analysis in steady state condition

High porewater pressure in downstream of dam foundation leads to high uplift pressure that eventually results in upheave or blow up. In general, this condition occurs if there is high permeability foundation layer under dam body or downstream bench. Failure is likely to occur when uplift pressure exceeds the corresponding overburden pressure. Piezometer is commonly used to monitor in downstream side.

To evaluate the potential of uplift, seepage analysis in steady state was performed using Geo-Studio 2019 as shown in Fig. 5. USBR [9] recommends factor of safety (FS) against uplift as large as 2.0 and 1.5 for new dams and existing dams, respectively. Analysis showed that uplift pressure at downstream was 200 kPa leading to FS of 1.76, which was less than 2.0. Thus, to fulfill the requirement, a fill of 3-m high and/or a relief well at downstream are proposed. Additionally. Two conditions, with and without secant pile, were analyzed. Using secant pile, seepage debit was reduced from 5.85 x 10^{-5} m³/sec/m to 1.6624 x 10^{-5} m³/sec/m.

Seepage can erode soil particle and lead to form of continuous pore like a pipe. This condition is termed as piping erosion that commonly occurs in foundation mass or cohesive fill. Many factors can be attributed to the occurrence of piping, including poor compaction. Frequently, control system is installed in the dam to continuously monitor areas that prone to seepage concentration.

FS against piping can be evaluated using ratio between critical exit gradient (i_c) to exit gradient. USBR [9] recommends a FS value of 4.0 and 3.0 for new and existing dams, respectively. FS against piping for dam without secant pile and with secant pile are 2.0 and 5.3, respectively.

5.2. Seepage analysis in transient condition

The effect of change in water level from normal elevation +100.00 m to el. +87.10 m on the stability of dam in rapid drawdown needs to be evaluated. During this transient condition, pore water pressure in the dam core is still high due different in water dissipation between core and fill zones. In general, rapid drawdown affects stability in the upstream zone. Rapid drawdown analysis in M Dam showed that FS reduced from 3.31 (el. +100.00 m) to 2.93 (el. +87.00 m) within 30 days.

5.3. Deformation analysis

Deformation analysis is needed to evaluate the dam deformation due to loading during construction, after construction, and normal water level condition. Figure 6 shows example of deformation analysis using Geo-Studio 2019. In this analysis, deflection and shear experienced by the capping beam and cut-off can also be evaluated.

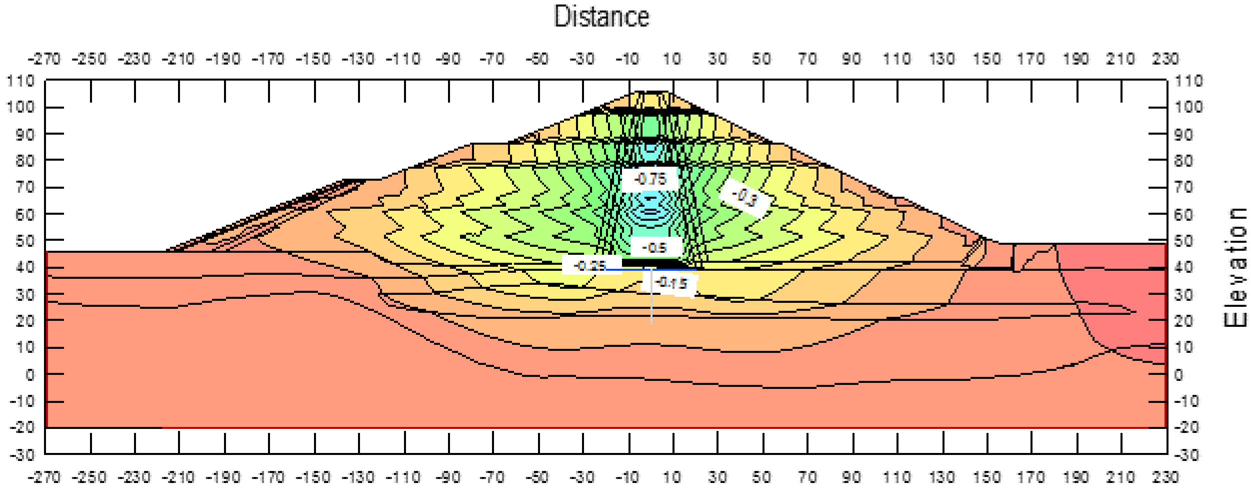

Figure 6. Example of deformation analysis in M Dam

6. Summary and conclusions

The M Dam construction is a good example when limited site characterization in the initial stage could have negative impact in the following stages. Having initial limited resource for site characterization, the extent of confined aquifer layer and weathered tuff layer was unidentified correctly. This resulted in incorrect decision in selecting dam foundation excavation level and the best solution for seepage-reduction method. Additional site characterization program had to be performed to propose new dam design after the results from trial grouting test for grout curtain construction was discouraging. The consequences in redesigning resulted in time and financial losses. Investing in considerable site characterization in the early stage can reduce uncertainties that eventually avoiding any bad impact.

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References

[1] Casagrande, A. "Control of Seepage through Foundations and Abutments of Dams", In: Geotechnique, Vol. 11 Issue 3, 1961, pp. 161-182. https://doi.org/10.1680/geot.1961.11.3.161

[2] Saito, K. "Study on Rock Mass Classification Method", CRIEPI Report, Volume U91059, pp.36, 1992. (in Japanese)

[3] Bell, F. G. "Open Excavation in Rock Masses", In: Bell, F. G, Henemann, B. (eds.) Engineering in Rock Mass chapter 21, 1992.

[4] Authorship "Indonesian Rockfill Design Guide – Volume 3 Foundation and Dam Design", Indonesian Ministry of Public Works & Housing, Chapter pp.22, 1999. (in Indonesian)

[5] Amos, P. D., Bruce, D. A., Lucchi, M., Watkins, N., and Wharmby, N. "Design and Construction of Deep Secant Pile Seepage Cut-Off Walls Under the Arapuni Dam in New Zealand," In: USSD 2008 Conference, Portland, OR, 2008.

[6] Newman, E., Forrest, M., Kegel, K., Pattermans, K. "Design and Construction of a Secant-Pile Cutoff Wall in Variable Ground Conditions", In: 35th Annual USSD Conference, Louisville, Kentucky, USA, 2015.

[7] Jordan, P. W., Pitchford, L."Beaver Dam Secant Pile Wall Completion Report", Department of the Army, Little Rock Districk: U.S. Army Corps of Engineers, Arkansas, United States, 1995.

[8] Simpson, D.E., Phipps, M., Ressi, A.L., "Constructing a cutoff wall in front of Walter F George Dam in 100 feet of water", Hydro Review, Volume 25, No 1, 2006.

[9] U.S. Department of Interior Bureau of Reclamation "Design Standards No.13, Chapter 8 (Seepage) phase Final", USBR, United States, 2014.