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Construction failure of X Dam: the importance of field monitoring

Andhika SAHADEWA[1,3], Haris SETYAWAN[1], Mahdi TANJUNG[1], Astyka PAMUMPUNI[1,3], Abi HAKIM[2], Jagad LANGIT[3], Pebri HERRY[1,4], Aris WIBOWO[1,4]

[1]Bandung Institute of Technology, Bandung, Indonesia
[2]Indonesian Institute of Technology, South Tangerang, Indonesia
[3]Indonesian Geotechnical Inztitute, Yogyakarta, Indonesia
[4]Nur Straits Engineering, Bandung, Indonesia
Corresponding author: Andhika Sahadewa (sahadewa@itb.ac.id)

Abstract

Hundreds of dam failures have occurred leading to environmental damages, massive property destruction, loss of lives, and economic lost. Dam failure during construction period has not been extensively reported as many as failures in operational period. This paper presents a case study of a dam construction highlighting that disparaging field monitoring may lead to a catastrophic failure. Field monitoring in a dam construction can capture deviation, variability, and complexity in a dam site that may not be able to be modelled in the design stage. Information from field monitoring plays vital role as it frequently becomes a basis in continuing the planned construction method or altering the construction method. X Dam, located in Indonesia, is an inclined-core fill type dam. This dam was under construction to reach 50-m tall with a total capacity over 1.5 M m^3. During dam embankment construction stage, it experienced 3 progressive slope failures within 2 weeks. This event was started by a 2-m shallow failure surface. The last event was the largest one comprising a 22-m deep seated failure. Investigating the failure source and redesigning the dam required considerable effort and resulted in time and financial losses. Numerous site investigations were performed, including Multi-channel Analysis of Surface Wave and Vane shear tests. Forensic analysis showed that the failure was associated with multi-root causes, including an excessively fast embankment construction, challenging fill compaction, halloysite fill material, high rain intensity, and very optimistic design parameters. These circumstances were corroborated by improper field monitoring performance. Immediate remediation steps, involving collapsed material removal and temporary drainage construction, were conducted to avoid detrimental condition. Several design alternatives were proposed to continue the construction. The X Dam construction showed that performing appropriate field monitoring can help us avoiding any imminent negative consequences as it also serves as an early warning system.

Keywords: Slope Stability, Dam Failure, Field Monitoring, Dam Construction

1. Introduction

Dam is a manmade barrier, generally constructed within a valley, that controls both surface and underground water flows. The idea of forming this water stream wall dates to 3,500 – 3,400 BC in Jordan, where Jawa Dam was built to take benefit of controlling water (Müller-Neuhof et. al. 2015). Dam offers many advantages to support human life, such as water supply, irrigation, flood control, energy source, and recreation. In growing concern for global water scarcity, many water reservoir alternatives, such as snowpack, are emerging. However, dam remains as reliable water storage and may be the important key factor in answering future water resource challenges.

Dams can provide significant contribution to the economic development and to the social welfare of a country. Nevertheless, benefits from a dam are always accompanied by potential risks due to natural hazards and human factors that can resulted in a dam failure. This failure incident is threat for people who live near a dam or who might be affected by a dam collapse. In addition, infrastructure surrounding the dam is also under this risk. Unfortunately, hundreds of dam failures have been documented and resulted in environmental damages, massive property destruction, loss of lives, and economic lost. Examples of recent notable dam disasters are summarized in Table 1.

Numerous dam incidents and collapses have occurred for as long as human has built dams. Dam failure is described as sudden and rapid uncontrolled discharge of stored water due to dam collapse or, in some instances due to an upstream land slide into the reservoir with or without dam collapse (Adamo et al. 2010). According to the Association of State Dam Safety Officials (2019), the root of dam failures is likely attributed to the following origins: (1), overtopping due to water spilling over dam crest, (2) foundation defects, such as slope instability as well as settlement, (3) cracking due to any displacements such as dam natural settling, (4) insufficient maintenance and preservation, and (5) piping.

Dam	Dam Type[a]	Country	Height (m)	Reservoir Vol. (Million m^3)	Date Built	Failure[b] Date	Failure[b] Type	No. of deaths
Vega de Tera	CMB	Spain	34	7.8	1957	1959	SF	144
Malpasset	CA	France	66	22	1954	1959	FF	421
Babii Yar	Emb	Ukraine	-	-	-	1961	OF	145
Vaiont	CA	Italy	265	150	1960	1963	LA	2600
Baldwin Hills	Emb	USA	71	1.1	1951	1963	IE	5
Frias	Emb	Argentina	15	0.2	1940	1970	OF	>42
Banqiao	Emb	China	118	492	1953	1975	OF	>10000[c]
Teton	Emb	USA	93	308	1975	1976	IE	11
Machhu II	Emb	India	26	100	1972	1979	OF	2000
Bagauda	Emb	Nigeria	20	0.7	1970	1988	OF	50
Belci	Emb	Romania	18	13	1962	1991	OF	25
Gouhou	Emb	China	71	3	1989	1993	IE	400
Zeizoun	Emb	Syria	42	71	1996	2002	OF	20
Camara	RCC	Brazil	50	27	2002	2004	-	5
Shakidor	Emb	Pakistan	-	-	2003	2005	OF	>135
Situ Gintung	Emb	Indonesia	16	2	-	2009	IE	100
Saddle Dam D	Emb	Laos	16	-	2017	2018	-	71

[a]CMB, concrete & masonry buttress; CA, concrete arch; Emb, embankment; RCC, roller compacted concrete
[b]SF, structural failure on first filling; FF, foundation failure; OF, Overtipping during flood; LA, 270 million m^3 landslide into the reservoir caused overtopping of the dam by a wave 125-m high, but the dam still survived; IE, Internal erosion.
[c]It was reported that tens of thousands died in this disaster, which involved the failure of a series of dams, of which Banqiao was the largest.

Table 1: Examples of notable dam disasters. (after Charles et al., 2010, Warren, 2010, and, The Collapse, *n.d.*).

Teton Dam, located on Snake River, Idaho, USA, is a noteworthy example demonstrating field instrumentation is very crucial in dam construction. It was a 93-m high earth fill dam that collapsed during first filling in 1976. The dam failure resulted in 296,000 m^3 water discharge. It was so fortunate that due to early warning and efficient evacuation, around 30,000 people living in the downstream could be saved. Nevertheless, the damage consequences were still significant, including 11 people lost lives. This failure was attributed to insufficient protection against foundation seepage as well as misinterpretation of the filling material properties. Advisory board for the failure investigation, including Prof. Arthur Casagrande and Prof. Ralph Peck, reported that Teton Dam should have been equipped with comprehensive field instrumentation system, including surface markers, settlement gauges, inclinometers, and piezometers. According to Silveira (2014), this system would allow detection of the piping progression much earlier. Although failure may not be avoided, it would have given longer preparation that may have substantially reduced damages in the downstream and avoided casualties.

Most articles reported dam failures during operational period. In fact, dam failures in the construction period also have occurred. Nevertheless, this type of construction incident is rarely known to public due to the following reasons: (1) incident is confidentially kept, (2) failure consequence is not as significant as that of failure during operational period, and (3) repair and mitigation are relatively easy. Examples of dam construction failures are listed in Table 2.

Carsington Dam, situated in between Wirksworth and Kniveton, Derbyshire, England, is a remarkable case of failure during construction. This dam was a 1225-m long, 35-m high earth fill embankment constructed from 1981 to 1984. According to Skempton (1985), the dam was simply about 1-m to the final crest elevation on Friday, 1 June 1984. Over the weekend there was no fill activity due to heavy rainfall period. On Monday, 4 June 1984 the upstream slope started to slip over a length of 190 m. On Thursday 7 June 1984, nearly 500 m section of the upstream slope slipped and resulted in a 15-m deep and 30-m wide gap along the crest. During construction, field monitoring was performed in Carsington Dam, in which a series of piezometer, settlement gauges, and strain gauges were installed. Nevertheless, failure to revise the design, based on the available test data and instrumentation readings as construction proceeded, was one of the reasons attributed to the collapse. As one of lessons learned from Carsington Dam, Rowe (1991) strengthened the urgency of selecting instrumentation that capable of indicating pre-failure signs.

Dam	Location	Construction	Year failed	Type of dam	Failure Origin
Calaveras	58 km SE of San Francisco, California, USA	1914 - 1925	1918	Semi-hydraulic earth	Concrete outlet tower toppled over
Puddingstone	Pomona, California, USA	-	1926	Hydraulic fill	Overtopping
Lafayette	Lafayette Creek, California, USA	1928	1928	Rolled earth	Foundation slide
Hell Hole	Rubicon River, California, USA	-	1964	Rock fill	Unprecedent rains
Carsington	Derbyshire, England, UK	1979 - 1992	1984	Earth fill	Chemical degradation of the fill materials

Table 2: Examples of dam failure during construction. (after Univ. California Davis, n. d.).

The cases of Carsington and Teton Dams show that the performances of a dam, foundation, reservoir, and river basin from investigation, design, construction, to operation phases are very crucial information for engineering evaluations. Instrumentation and field monitoring can offer such information comprehensively. In addition, field monitoring can capture deviation, variability, and complexity that may not be able to be known in the earlier stage. According to Prasad and Dixit (2019) the following requirements must be considered in selecting instruments: (1) precise, (2) easy-operable, (3) durable, and (4) repairable and replaceable. Additionally, field monitoring frequency should be high enough to capture any measured parameter variations with time.

X Dam, located in Jawa, Indonesia, experienced catastrophic failure during its construction in 2021. This manuscript describes failure incident, investigation, and post-failure mitigation of the dam. Disordering field monitoring execution was one reasons of the collapse. Authors believe that investigation report of such failures can contribute to advances in design, construction, operational and monitoring of dams.

2. The Design of X Dam

The idea of building X Dam, designed mainly for flood control, has been initiated since 1990s. But the construction was not commenced until 2017. Prior to the failure incident, this dam was originally designed to be approximately 50-m high, 170-m long, and 10-m wide with an inclined-core fill (Figure 1). Having capacity exceeding 1.5 million m^3 and inundation area of more than 5 Ha, this dam is expected to reduce flood debit over 10 m^3/second.

Geologically, the X dam is situated in lahar breccia as part of Quaternary volcanic unit product of a nearby active volcano. This breccia consists of lahar, lava, andesite, and basalt. Lahar breccia in X Dam is characterized by poorly sorted small to large boulder fragment with coarse ash to lapilli matrix. This lahar breccia was deposited in Holocene time and experiencing low to minimal compaction and cementation. Hence, it is still in loose condition and easily eroded.

X Dam in fact is equipped with a series of dam instrumentation, including standpipe piezometers, surface monuments, and inclinometers with multilayer settlement. Instrumentation locations are presented in Figure 1, Figure 2, and Figure 3.

3. Construction Failure Incident and Slope Failure Investigation

During random fill construction stage, the downstream slope of Dam X experienced 3 progressive slope failures within 2 weeks (Figure 4). This event was started by a 2-m shallow failure surface (EL. 563 to EL. 561.7) occurred on 30 September 2021. This incident was followed by much deeper slope failure with slip surface from EL. 578 to EL. 561.7 on 5 October 2021. The last incident was the greatest one comprising a 22-m deep seated failure (EL. 584 to EL. 561.7) on 13 October 2021.

Although X Dam failure did not cost life and injury, investigating the failure sources required extensive effort and resulted in time and economic losses. A variety of post-failure site investigations were performed. Vane shear tests were performed to evaluate the shear strength of materials post-failure in 3 locations. The residual shear strength of random material around the downstream toe (EL. 563 to EL. 564) ranged from 4 kPa to 5.6 kPa with average value of 4.6 kPa. At EL. 570 to EL. 572, the shear strength of random material varied from 0.1 to 9 kPa with average 4.9 kPa. The shear strength of core material at the crest ranged from 39 kPa to 55 kPa with average value of 47 kPa. A series of Multi-channel Analysis of Surface Wave (MASW) testing was conducted in the failure surface. In general, MASW results showed that shear wave velocity values in the first upper 30-m is about 160 m/s on the average. This relatively low value indicated that the random fill can be classified as soft soils according to various references, including ASCE 7-16 (2017), Indonesian national standard/SNI 1726 (2019), and Madun et al. (2016). This observation suggested that the failure body mass reach to 30-m deep or the soil was indeed not compacted very well.

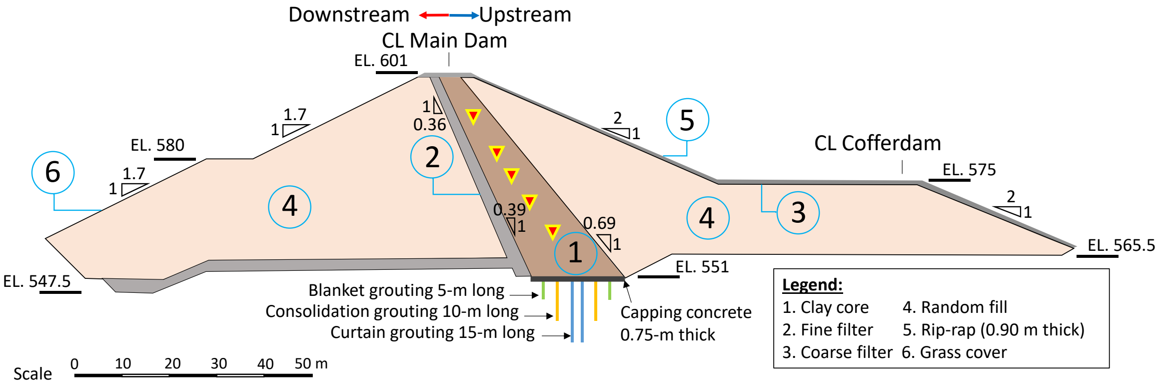

Figure 1: Cross-section of X Dam at STA 0 + 235.

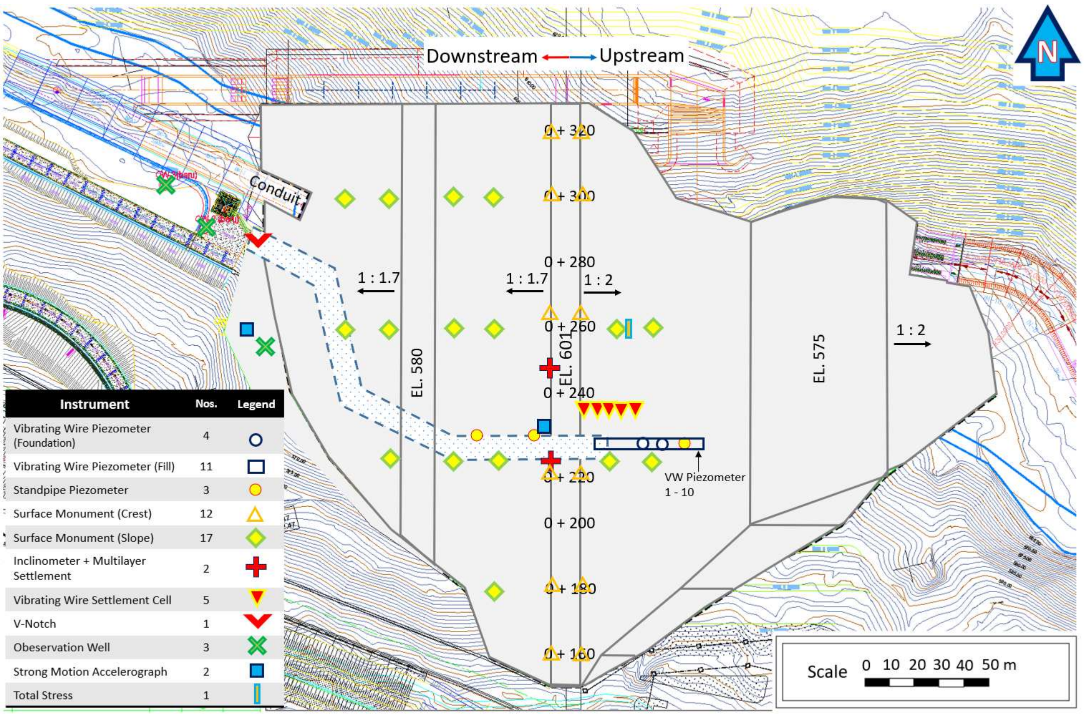

Figure 2: Plan view of X Dam.

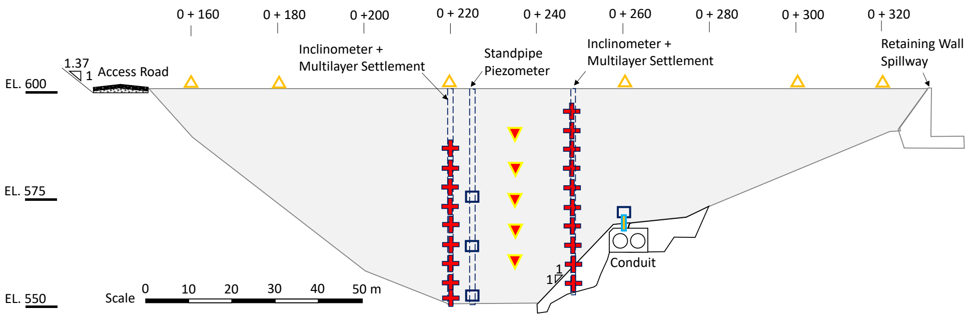

Figure 3: Long-section axis view of X Dam.

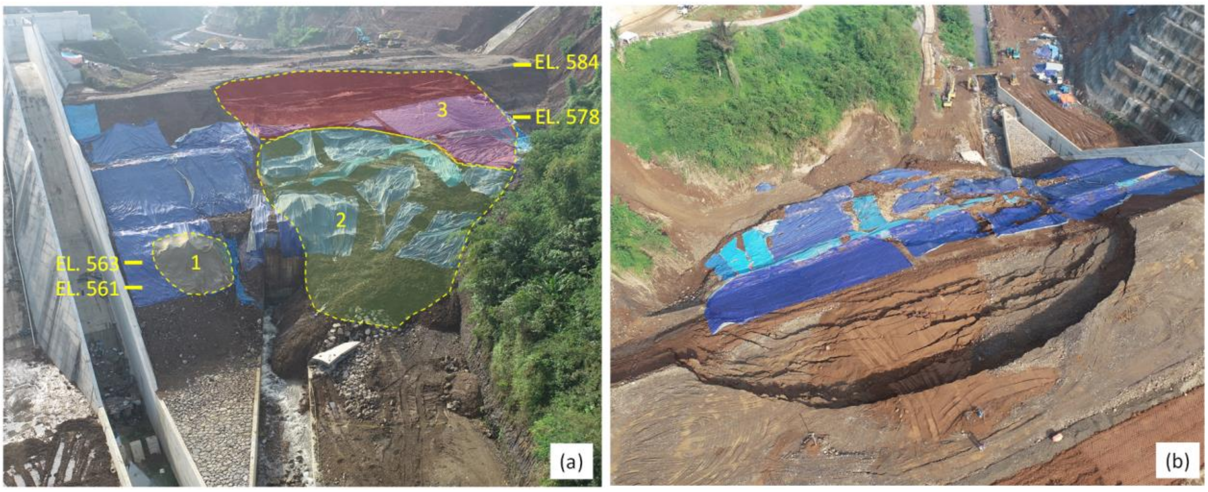

Figure 4: Downstream slope failures in Dam X: (a) view from downstream and (b) aerial view.

Prior to the failure incident, the random fill compaction was very challenging. The X Dam is located in high rainfall intensity region leading to compaction work results that generally exceeded the wet optimum side. Thus, the optimum density was difficult to achieve. Nevertheless, the compaction work quality control using sand cone test showing very promising results, which was in the order of 120% of maximum dry density. In fact, walking on the compacted random fill indicated that the ground was still very soft. To investigate this discrepancy, Indonesian Geotechnical Inztitute performed 3 in-situ large scale direct shear tests in the random material to evaluate the shear strength of random fill material (Figure 5 and Figure 6). The direct shear test suggested that the strength was relatively low. X-Ray Diffraction test showing that random fill material contained Halloysite which belongs to the kaolin group. This mineral is well known for rapid water sorption (White and Pichler, 1959). The presence of Halloysite explained reason compaction results that easily exceeded wet optimum.

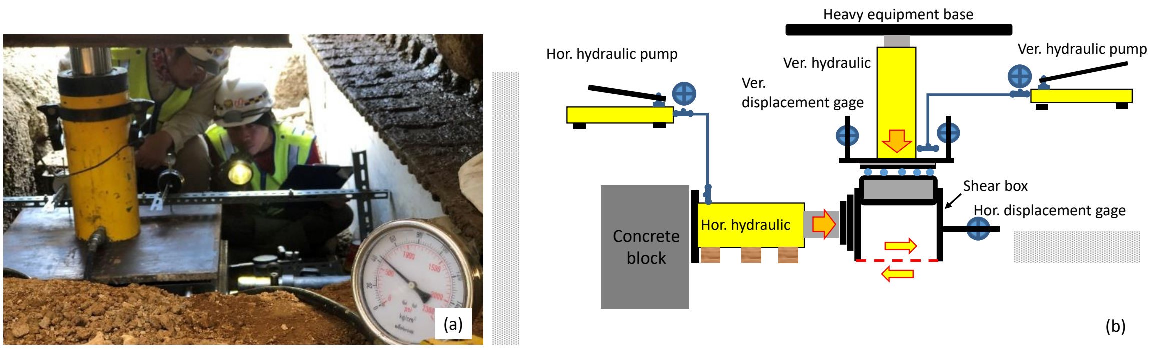

Figure 5: In-situ large scale direct shear test on random fill material: (a) field test and (b) testing setup

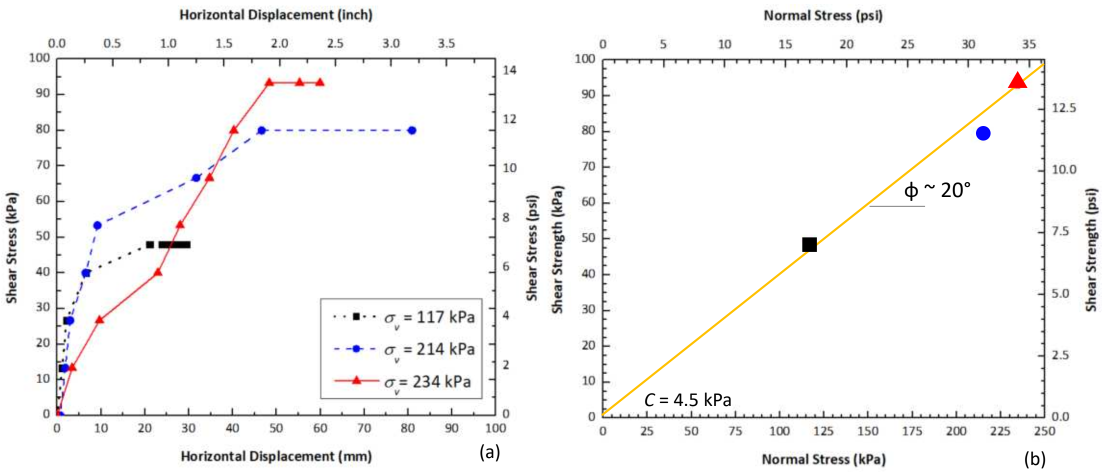

Figure 6: In-situ large scale direct shear test results on random fill material.

It was very challenging to substitute random fill materials from different quarry despite this finding. Instead, the strategy was blending the current random material with 50% gravelly sand for constructing random fill from EL. 566.5 above. The blending was not performed using a special equipment. Instead, it was simply performed using excavator. This method left homogeneity of blending material questionable. Nevertheless, it was thought that mixing the native random fill material with gravelly sand can reduce water sorption behaviour hence increasing the compaction work performance. Since blending application, the random fill embankment construction was performed excessively fast.

Difficulty in compaction works has distracted other crucial works in X Dam construction, including field monitoring and design review. Prior to the incident, faulty instruments were not repaired. Unfortunately, standpipe piezometer nearby the slope failure was also damaged. In addition, field monitoring data was not comprehensively and carefully interpreted. This circumstance resulted in the undetected embankment movement. Furthermore, design review was not conducted despite pessimistic compaction work results.

3. Post-failure Mitigation and Lesson Learned

Post-failure mitigation for X Dam included immediate remediation and dam redesign. The immediate mitigation steps were removing collapsed material and constructing temporary drainage to avoid unfavourable condition. The following design alternatives were proposed to continue X Dam construction:

- Alternative 1: Reducing downstream slope to 1V : 2.5H in EL. 551 to EL. 576, reducing downstream slope to 1V : 2H in EL. 576 to EL. 601, constructing counterweight at downstream toe using stone, and relocating V-notch system
- Alternative 2: Changing downstream embankment material to stone, and maintaining the downstream slope as 1V : 1.7H
- Alternative 3: Changing downstream embankment material to stone (40%) and gravelly sand (60%), and maintaining the downstream slope as 1V : 1.7H

In addition to these 3 design options, the v-notch water seepage channel was altered from pumping system to gravity channel. A prefabricated vertical drain (PVD) system was proposed to be installed in several design scenarios. First, PVD installation is proposed in the downstream and upstream embankment made from random fill containing Halloysite that remained unaffected by the failure incident. Second, PVD is proposed for the design alternative that still allows random fill containing Halloysite in the following construction. It was also emphasized that additional instruments and strict field monitoring execution should be performed.

Post-failure investigation showed that the failure was attributed to multiple reasons, including an excessively fast embankment construction, challenging fill compaction, halloysite fill material, high rainfall intensity, and very optimistic design parameters. Additionally, inadequate field monitoring performance resulted in unobserved embankment movement. Many Lessons can be learned from this incident, including:

- Field monitoring should be performed by a team that has capability to collect data, review data, and interpret data comprehensively.
- Should any construction difficulties that can deviate design assumption and parameters occur, field monitoring frequency should be increased accordingly while solutions for construction difficulty are explored.
- Inclinometer should also be installed in downstream and upstream slopes, not only along the dam axis
- Safety threshold values for all instrument readings should be stated clearly.
- The design and its factor safety should be re-evaluated when current strength and performance data are obtained.

4. Conclusion

Dam is an important infrastructure that can support human in managing water. The presence of dam offers a variety of benefits, ranging from energy source to recreational place. Nevertheless, these advantages are always accompanied by potential hazards associated with dam failures. In many cases, we have even observed a long history of dam incidents and failures that have cost life. In addition to failures during construction, dam can also collapse in its construction stage, such as X Dam failure in Indonesia.

Experiences learned from the X Dam construction failure showed that, as construction progressed, a dam design should be revised, if necessary, based on current material test and field monitoring results. Additionally, field instrumentation planning should accommodate extra instrumentation, particularly in critical spots, in case faulty sensors are detected. Lastly, field monitoring should be conducted frequent, sufficient, and regular to help preventing any imminent negative consequences as it also serves as an early warning system. To conclude this article, rigorous supervisory controls should be conducted to confirm that dam construction and operation is managed properly through advisory, monitoring, surveillance, and regular independent review.

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