

Cost Aspect in the Stability Analysis of an Earthfill Dam with Respect to Variations in Embankment Materials and Water Levels (Case Study: Cibeeet Dam Project, Bogor Regency)

Muhammad Faizal*, Muhammad Zaki

Universitas Trisakti, Indonesia

Email: muh.faizal1981@gmail.com, m.zaki@trisakti.ac.id

Keywords

Embankment dam; fill material variation; seismic analysis; earthquake duration; safety factor.

ABSTRACT

Stability analysis was carried out using PLAXIS 2D based on the Finite Element Method with the Shear Strength Reduction (SSR) approach. Two design alternatives were evaluated: Model 1 with a complete material zoning system consisting of sand-gravel, sandstone, and coarse filter layers, and Model 2 with a simplified configuration dominated by sandstone material. The evaluation was performed under Low Water Level (LWL), Normal Water Level (NWL), and Flood Water Level (FWL) conditions, as well as under static loading, Operating Basis Earthquake (OBE), and a design earthquake with a magnitude of 7.5. The results indicate that increasing reservoir water levels and seismic loading lead to a reduction in the Safety Factor (SF); however, all analyzed conditions still satisfy the required stability criteria. Model 2 exhibits higher SF values under static conditions, while Model 1 demonstrates superior stability performance under strong earthquake loading and long-duration seismic events. Cost analysis shows that the total construction cost of Model 1 is IDR 566.85 billion, whereas Model 2 requires IDR 558.86 billion, resulting in a cost saving of 1.41% for Model 2. The integrated analysis reveals a clear trade-off between stability and cost, where Model 1 provides higher technical safety, while Model 2 offers greater economic efficiency.

INTRODUCTION

The development of water resource infrastructure, especially dams, plays an important role in supporting water security, flood control, raw water supply, and hydroelectric power plants (PLTA). In Indonesia, which has high rainfall and fluctuating river flow patterns, dams are one of the strategic solutions to ensure year-round water availability and reduce damage from hydrological disasters (Jayanti et al., n.d.; Luo et al., 2022; Rejekiingrum et al., 2022).

Dams are vital infrastructure with an important role in water resource management, including irrigation, raw water supply, and hydropower generation (Digna et al., 2018; Dillon & Fishman, 2019; Kim et al., 2018). The Cibeeet Dam in Bogor Regency, as an urugan-type (earthfill) dam, must have high stability to avoid potential failures that could cause major disasters for the surrounding community. Factors such as variations in embankment materials, water levels, and earthquake loading are crucial aspects in determining dam stability (Gordan et al., 2022; Zhou et al., 2023).

In the Cibeeet Dam project in Bogor Regency, the planning and implementation of material stockpiles consist of several zones, including impermeable cores, filters, drainage layers, and shell zones (outer zones). Each zone has its own technical requirements in terms of gradation, permeability, and shear strength (Bock et al., 2019; Mneina & Shalaby, 2020).

However, in practice, there are several technical challenges, such as limited supply of materials meeting specifications, inconsistencies between laboratory and field test results, and variations in mechanical properties due to the natural conditions of material sources (Bock et al., 2019; Seifi et al., 2017; Wang et al., 2020). These issues have the potential to affect the overall slope stability of the dam.

Water infrastructure is a critical asset whose function must remain optimal at all times. Therefore, such structures must be designed to safely withstand loads under both normal and extreme conditions, ensuring continued operation under design load events and preventing loss of life under extreme loading (Bedon et al., 2018; Paik, 2019; Travush et al., 2016). One of the key loads that must be considered under both operating and extreme conditions is seismic loading. Large earthquakes are rare; however, if they occur and the dam is not adequately designed to resist them, the resulting risk is unacceptable (Lin et al., 2015; Wieland, 2016).

Through a case study of the Cibee Dam in Bogor Regency, this study aims to analyze the stability of an urugan (earthfill) dam by considering three main variables: (1) variations in embankment material characteristics, (2) changes in water levels, and (3) earthquake loading. This research is expected to contribute to technical decision-making during the design, construction, and maintenance stages of dams, as well as to justify the need for technical evaluation when deviations from the initial material specifications occur (Costa et al., 2016; Li et al., 2024).

Indonesia, located in an active tectonic zone, frequently experiences earthquakes of varying intensities. Therefore, stability analysis under seismic loading is necessary to ensure that dams can withstand extreme conditions. In addition, variations in stockpiled materials and water levels can significantly affect dam safety factors (Salamah et al., 2023; Zhi et al., 2023). This study aims to analyze the stability of the Cibee Dam in Bogor Regency based on these variations.

In dam stability analysis, commonly used methods include the Limit Equilibrium Method (LEM) and the Finite Element Method (FEM). LEM is used to determine slope safety factors (SF) using force and moment equilibrium approaches, while FEM can be used to predict deformation and stress distribution within dam structures due to external loads such as earthquakes. These two methods complement each other in providing a more comprehensive understanding of dam stability conditions.

The novelty of this research is fivefold. First, it is the first study to integrate cost analysis directly with stability analysis for the Cibee Dam, quantifying the cost difference (1.41%) between two material configurations. Second, it analyzes the effect of earthquake duration (not just magnitude) on safety factors using historical seismic data from approximately 200 years to establish magnitude–duration correlations. Third, it directly compares two distinct material configurations: Model 1 (sand–gravel upstream, sandstone downstream) versus Model 2 (sandstone-dominant on both sides). Fourth, it evaluates stability under three water level conditions (LWL EL +67.75 m, NWL EL +80.00 m, FWL EL +84.36 m) and three loading scenarios (static, OBE, and 7.5 SR earthquake). Fifth, it provides cost–volume calculations based on actual unit prices from the project’s RAB.

The stability study of the Cibee Dam in Bogor Regency is increasingly relevant considering that climate change may impact rainfall variability and inflow discharge into the reservoir. Climate change can increase the frequency of extreme events, such as heavy rainfall,

which may accelerate erosion and increase hydraulic loading on the dam. This condition requires more in-depth study of extreme scenarios to ensure that dams remain safe under various operating conditions.

In the context of dam planning and management, the results of this study are expected to provide useful technical recommendations for those responsible for dam operation and maintenance. By understanding the factors that affect dam stability, more appropriate mitigation measures can be implemented to prevent potential failures that could cause major losses to communities and the surrounding environment.

Therefore, this study aims to analyze the stability of the Cibeet Dam in Bogor Regency with respect to variations in embankment materials, water levels, and earthquake loading, as well as to analyze the comparative construction costs associated with these material variations. Thus, a comprehensive stability analysis of the urugan dam, considering these three main parameters, is essential to ensure the long-term success of the Cibeet Dam Development Project in Bogor Regency, as well as other similar dams in Indonesia.

The main objective of this study is to analyze the slope stability of the Cibeet Dam in Bogor Regency by considering variations in embankment materials, water level fluctuations, and earthquake loading. Specifically, this study focuses on analyzing the effect of material variations on slope stability using PLAXIS software-based numerical modeling, evaluating the impact of water level changes on slope safety factors, and assessing the effect of seismic loading on dam stability using the finite element method. In addition, this study aims to provide applicable technical recommendations to improve the long-term safety and resilience of the Cibeet Dam, as well as to analyze the combined influence of material variation, water level fluctuation, and earthquake loading on estimated construction costs.

The benefits of this research include improving the quality of dam design and safety through the selection of appropriate and cost-effective materials for construction, enriching references and learning in the fields of geotechnical engineering and construction management in dam engineering, and supporting the formulation of technical policies in dam management, risk evaluation, and disaster mitigation to ensure the safety and sustainability of water resource infrastructure.

METHOD

The Cibeet Dam is located in Bogor Regency, West Java, and is planned as one of the national strategic dams for irrigation purposes, raw water supply, flood control, and hydroelectric power plant (PLTA) potential. This dam is a zonal type of irrigation with a watertight core of clay core, equipped with filter, shell, and drainage zones.

Geologically, the location of the dam is dominated by layers of sandstone, naples, and alluvial material in the river valley area. The condition of the foundation is relatively good, although there is a potential for seepage due to the presence of permeable navel and sandstone coatings. This is a concern in stability planning and seepage force calculations. In the planning process, the stability of the Urugan dam is greatly influenced by various factors, including the type of backfill material used, variations in the water level and the dynamic load (earthquake) that occurs during dam operation.

This study aims to analyze the relationship between the variation of backfill materials, changes in water level and earthquake load on the stability of the urugan-type dam, as well as

how these two factors affect the construction cost aspect. In this study, slope stability modeling will be carried out using geotechnical software, namely Plaxis for several scenarios of a combination of heap material, water table height and earthquake load. Each scenario was analyzed for its safety factor value to determine stability conditions. Furthermore, a comparative analysis of construction costs from each scenario was carried out to evaluate the trade-off between technical and economic aspects.

The geological conditions at the dam location and inundation areas are all occupied by rocks from the Kalibeng Formation in the form of sandstone, clay and Miocene-aged limestone which on the surface has weathered 1-5 m thick. Meanwhile, in the watershed, there are alluvial units and some river levels are 1-3 m thick.

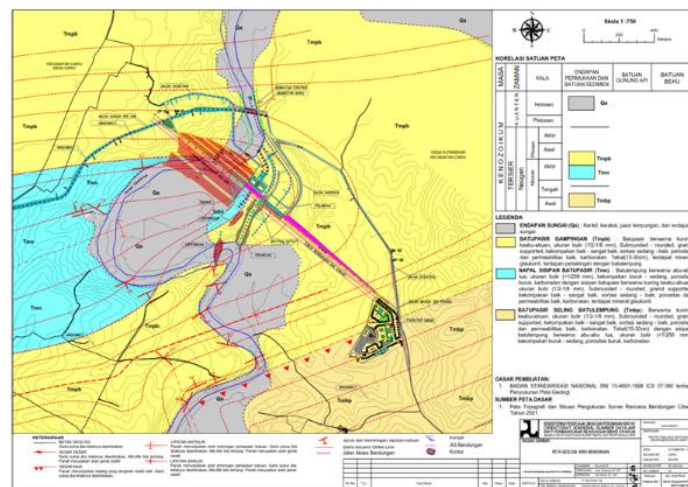


Figure 1. Geology of the Cibeeet Dam
(Source: Cibeeet Dam Planning)

At the bottom of the river (river bed), the dam foundation rests on a medium hardness nabal stone interlude. The dam site on the riverbed revealed bedrock that is napal, and in some places there are relatively thin river deposits of less than 3 m. On the right side of the riverbed there is a river level (terrace) 1 to 3 m thick that covers the bedrock while on the left is covered with thin weathering soil between 1-3 m which must be removed because it is soft with low carrying capacity.

So the depth of the foundation that must be dug at the bottom of the river is as deep as it is to find fresh rocks in the form of napal stones. Foundation rocks have a strong weathering rate up to (Highly Weathered-HW) a moderate weathering level (Moderately Weathered-MW) with a weak hardness level (Weak-W), or a weathering level (CL) or a uniaxial compressive strength value ranging from 20 kg/cm² to 80 kg/cm² as the bearing capacity of the foundation, while weathered ones with a weak hardness (Weak-W) or soft (D) or < 20 kg/cm² must be discarded. The foundation rock alternates between water escape and is relatively impermeable with a permaability value (k) from the surface to a depth of 10 m ranging from 1-5 lugeons, while a depth of 10-20 m has a value of 5-15 lugeons.

On the left back, the dam foundation also rests on the interplay of limestone and medium hardness. The dam site on the left backrest is covered by relatively thin weathering soil ranging from 1-3 m. Foundation rocks have a strong weathering rate up to (Highly Weathered-HW)

moderate weathering level (Moderately Weathered-MW) with a weak hardness level (Weak-W), or a weathering level (CL) or a uniaxial compressive strength value ranging from 20 to 80 kg/cm² as the bearing capacity of the foundation, while weathered ones with a weak hardness (Very Weak-VW) or soft (D) or < 20 kg/cm² must be discarded. The foundation rock alternates between escaping water and being relatively impermeable with a permeability value (k) from the surface to a depth of 10 m has a value of 5-15 lugeons (moderate). Depths of 10-30 m have a lugeon value of 1-5 (low).

This study uses primary and secondary data as follows:

Primary Data

Soil Properties test data which includes specific gravity, water content, volume weight, soil consistency limit and gradation.

Secondary Data

Technical design data of the dam from the DED (Detail Engineering Design) document which includes:

1. Data from soil laboratory tests: including gradation tests, volume weight, moisture content, shear strength (UU).
2. Field test results data: such as Standard Penetration Test (SPT), Cone Penetration Test (CPT), and geoelectricity (if available).
3. Topographic data and dam geometry.
4. Modeling data from PLAXIS (FEM simulation) software.
5. Unit price of excavation, stockpile and compaction work
6. Actual tool and labor productivity data in the field (types and sources)

Historical data of the water table.

1. Planned earthquake load data (PGA, response spectrum).
2. Supporting scientific literature and journals.
3. Standard price data for materials, tools and wages (HPS)

Research Methods

This type of research is an experimental quantitative research, which uses a numerical simulation approach with PLAXIS 2D software based on the Finite Element Method (FEM) to analyze the stability of the dam. The research was conducted with the following variation scenarios:

1. Variations of backfill materials: coarse, medium, fine materials (based on gradation and mechanical parameters).
2. Water table variation: minimum, normal, and maximum conditions.
3. Earthquake load variations: No Earthquake, OBE Earthquake, 7.5 SR Design Earthquake

Research Variables

In this study, the research variables were arranged to provide clear boundaries regarding the factors tested, the parameters that were affected, and the aspects that were controlled during the analysis process. These variables are necessary so that the analysis method can run systematically, measurably, and produce consistent interpretation.

In general, the research variables are divided into three groups, namely the independent variable, the bound variable, and the control variable.

Independent variables are variables that are deliberately changed or varied in research. In this study, independent variables included:

1. Difference in the configuration of the backfill material between Model 1 and Model 2,
2. Variations in reservoir water level conditions (LWL, NWL, and FWL),
3. As well as earthquake loading conditions (no earthquake, OBE earthquake, and 7.5 SR earthquake).

These variables were chosen because they greatly affect the stability of the dam and the distribution of forces in the dam body.

Dependent variables are variables that are influenced by independent variables. In this dam study, the bound variables include:

1. Safety Factor (SF) value,
2. Total deformation of the dam body,
3. Collapse field pattern,
4. As well as the total cost of construction of the heap material based on the results of volume analysis and unit price.

Bound variables are used to determine the effect of backfill material changes on stability and cost efficiency.

Controlled variables are variables that are kept constant so that they do not affect the results of the research. In this study, control variables included:

1. Same dam geometry for both models,
2. The soil parameters of each zone are used consistently,
3. The analysis method uses FEM (Finite Element Method) through PLAXIS 2D,
4. As well as uniform boundary conditions and analysis procedures.

With a clear and structured set of variables, this study can focus on evaluating two main aspects, namely dam stability and construction costs, as well as conducting a comprehensive comparison between Model 1 and Model 2. The following research variables are explained in Table 1 as follows.

Table 1. Research Variables

Variable Type	Variable Name	Variable Description	Observed Indicators/Parameters
Independent Variables	Variety of Stockpile Materials	Zoning configuration differences between Model 1 and Model 2	- Number of material zones- Type of random fill (<i>sand-gravel</i> vs sandstone) - Presence of coarse filter (Model 1)
	Water Level Variation	Reservoir water level elevation	- LWL (EL +67.75 m) - NWL (EL +80.00 m) - FWL (EL +84.36 m)
	Earthquake Load	Types of seismic loading applied	- No earthquakes - OBE Earthquake - 7.5 SR Earthquake
Bound Variables	Safety Factor (SF)	Stability values generated from PLAXIS	- SF without earthquakes - SF OBE - SF 7.5 SR
	Dam Deformation	Deformation response due to material and load variations	- Maximum deformation - Displacement pattern - Critical deformation location
	Construction Costs	Total material cost of the backfill	- Cost per zone - Total cost of Model 1 - Total cost of Model 2 - Cost difference (%)
Control Variables	Dam Geometry	Geometry is kept constant for both models	- Height, top width, slope slope

Variable Type	Variable Name	Variable Description	Observed Indicators/Parameters
	Soil Parameters	Geotechnical parameters of each zone	- c, ϕ, γ, E, v, k
	Analysis Method	The FEM PLAXIS method is used consistently	- <i>Phi-c reduction- Mesh & boundary conditions</i>

Data collection in this study was carried out through several stages that complemented each other, namely field studies, laboratory studies, documentation studies, and literature studies. Field studies include observation of geological conditions, topography, and construction activities at the project site, soil sampling from each reservoir zone to be tested in the laboratory, collection of data on unit prices of excavation, landfill, and compaction work, and observation of the operation pattern of production equipment on the work. Laboratory studies are carried out through soil testing to obtain geotechnical parameters such as cohesion (c), deep shear angle (ϕ), and modulus of elasticity (E), as well as maximum density and permeability tests. The documentation study includes data collection from planning consultants and project implementers, including technical designs, geotechnical reports, and topographic maps. Meanwhile, literature studies are carried out by examining the results of relevant previous research and referring to national and international journals as a theoretical basis and comparison of research results.

The data analysis in this study was carried out quantitatively through several systematic stages. The initial stage begins with geotechnical modeling, where dam models are compiled based on actual geometric data and geotechnical parameters, the zoning of the reservoir is modeled according to the existing design, and boundary conditions and loading are determined. Furthermore, stability simulations were carried out using PLAXIS 2D software with the phi-c reduction method for static analysis and dynamic time history for earthquake conditions, where each variation was tested in several combinations. The next stage is the calculation of the cost analysis, which includes the calculation of the productivity of the tools for excavation, stockpiling, and compaction work on each variation of the material, as well as the calculation of the construction cost for each of these variations. The simulation results were then interpreted by comparing the safety factor (SF) values of each scenario, determining the most stable and most critical combinations, identifying deformations that occurred both horizontally and vertically, and comparing the construction costs of each material variation to the greatest SF value. The final stage is drawing conclusions, namely by determining the significant influence of each variable studied (materials, water levels, and earthquakes) and testing the hypotheses that have been formulated in the previous chapter.

RESULTS AND DISCUSSION

Stability Analysis Results Using PLAXIS

This subchapter presents the results of the analysis of the stability of the body of the urugan dam using PLAXIS 2D software with the Finite Element Method (FEM) method to obtain the value of safety factors (ΣM_{sf}) at various water level conditions and earthquake loading. This analysis was conducted for both models of heap material, namely Model 1 (combination of sand-gravel and sandstone) and Model 2 (sandstone dominant), with the aim of evaluating the influence of material type on dam stability performance.

Numerical modeling was carried out on three water level conditions that represent the operational state of the reservoir, namely Low Water Level (LWL), Normal Water Level (NWL), and Flood Water Level (FWL). Each condition was then analyzed on three loading scenarios: no earthquake (static), OBE earthquake, and magnitude 7.5 SR earthquake. Thus, there are a total of nine analysis scenarios for each model.

The results of the PLAXIS analysis provide a comprehensive overview of the dam's stability response to variations in hydraulic and dynamic conditions. The SF value is calculated based on the numerical failure conditions that arise when the shear strength parameter of the material is gradually reduced until there is no longer a force balance that the model can maintain. With this method, an SF value is obtained that describes the actual stability capacity of the structure at each variation of conditions.

At the elevation of the LWL, the SF value reached 1.911, which is the highest value under static conditions. This is because in the LWL the hydrostatic pressure on the upstream slope is relatively small, so that the effective shear strength does not experience a significant decrease. In addition, the use of sand-gravel in the upstream zone helps to maintain stable stress conditions due to high drainage which is able to reduce pore water pressure.

When the water level rises to the NWL, the SF value decreases to 1.822, indicating an increase in water pressure on the upstream slope that reduces stability. In the FWL condition, the SF was at a value of 1.752, which is the lowest value in static conditions. Despite the decrease in stability, the entire SF value > 1.50 , so the static condition is still in the safe category according to ICOLD and SNI standards.

The decrease in SF from LWL to FWL reflects the general behavior of the urugan dam, where the pore water pressure in the core and filter layer increases with the rise in the reservoir water level, thereby decreasing the effective shear strength in the transition zones.

The SF value remained above the minimum limit of 1.10, indicating that the Model 1 was still safe against major earthquake conditions.

The SF value in the LWL is the lowest (1.330), in the LWL, the lack of hydrostatic pressure causes the upstream slope to not get a buffer effect from the water, so the dynamic response to deformation becomes greater.

SF increases at NWL (1.380), at this elevation, the water pressure contributes slightly to external stability, but not as large as in FWL.

The highest SF score was in FWL (1.467). This is in line with the phenomenon that high hydrostatic pressure helps reduce deformation downstream when earthquake vibrations occur.

Stability Analysis of Variations in the Duration of Earthquakes of 7.5 SR

In this study, the dam stability analysis was focused on earthquakes with a magnitude of 7.5 SR, which were selected as design earthquakes based on the results of regional seismic studies and considered the risk level and service life of the dam. The selection of constant magnitude aims to isolate the effect of earthquake duration on dam stability performance, so that the influence of duration variables can be evaluated more specifically and controlled.

In contrast to the pseudo-static approach which only represents the earthquake load in the form of static earthquake coefficients, the analysis in this sub-chapter examines the response of dams to variations in shock duration while still using the same magnitude parameters. This approach is based on the fact that two earthquakes of the same magnitude can produce different structural responses when they have different shock durations.

To support this analysis, historical data on earthquake events over ± 200 years in the study area was collected and processed. From these data, an empirical relationship between earthquake magnitude and shock duration was obtained through linear regression analysis. This relationship was then used to determine several variations in earthquake duration representing the 7.5 SR earthquake event scenario, which was then applied as an earthquake load on numerical modeling using PLAXIS software.

Stability analysis of earthquake duration variations was carried out at Normal Water Level (NWL) water level conditions, considering that this condition is the most representative operating condition during the service life of the dam. Stability evaluation was carried out on two dam models, namely Model 1 and Model 2, which have different material configurations and landfill zoning.

The area of dam study is located in an area that is tectonically active, particularly influenced by the subduction system of the Indo-Australian Plate against the Eurasian Plate in the south of Java Island. Therefore, understanding the characteristics of historical earthquakes is an important basis in analyzing the stability of dams to earthquake loads.

Based on tracing historical seismic data over a period of ± 200 years, 22 significant earthquake events were obtained that had a direct or indirect impact on the study area. The data includes information on the date of the incident, the location of the epicenter, the magnitude of the earthquake (Richter Scale), the duration of the shock, and the affected area.

In general, the magnitude of the earthquake recorded was in the range of 5.0 SR to 7.7 SR, with the duration of the shock ranging from 10 seconds to 60 seconds. Earthquakes with a large magnitude (≥ 7.0 SR) have been recorded several times in the southern West Java region, which shows the potential for seismic hazards that need to be taken into account in the design and evaluation of dam stability. The following is historical data on earthquake events in the study area described in Table 4.10 as follows.

Table 2. Historical Data on Earthquake Events in the Study Area

NO.	DATE	LOCATION	MAGNITUDE(SR)	DURATION(s)
1	September 11, 1921	South West Java	7.0	60
2	03 April 1924	Garut, West Java	6.5	30
3	June 28, 1937	Tasikmalaya, West Java	6.8	40
4	July 23, 1943	Tasikmalaya, West Java	6.8	40
5	January 14, 1958	Cirebon, West Java	6.2	25
6	01 February 1965	South West Java	6.0	20
7	February 10, 1977	Pangandaran, West Java	6.8	30
8	09 April 1982	Indramayu, West Java	5.9	15
9	July 21, 1990	Majalengka, West Java	5.8	15
10	August 02, 1999	Sunda Strait	6.5	20
11	June 4, 2000	Sukabumi, West Java	5.9	20
12	July 17, 2006	South West Java	7.7	30
13	August 02, 2007	South West Java	6.4	25
14	September 02, 2009	Tasikmalaya, West Java	7.0	60
15	04 September 2012	Sukabumi, West Java	5.7	15
16	December 15, 2017	Tasikmalaya, West Java	6.5	10
17	23 January 2018	Lebak, Banten	6.1	15
18	02 August 2019	Sunda Strait	6.9	20
19	10 April 2020	Sukabumi, West Java	5.4	10
20	November 21, 2022	Cianjur, West Java	5.6	10
21	03 January 2024	Bayah, Sukabumi	5.9	20
22	September 18, 2024	West Java	5.0	15

The results of the analysis of dam stability on the variation in earthquake duration with a fixed magnitude of 7.5 SR show that the duration of the earthquake shock is a parameter that significantly affects the value of the safety factor (SF), even though the magnitude of the earthquake has not changed. These findings indicate that it is not enough to evaluate the stability of dams only considering the magnitude or acceleration of the earthquake peak, but also need to take into account the length of time the earthquake energy acts on the dam structure.

Based on the results of numerical modeling using PLAXIS, it can be seen that the increase in earthquake duration in general is followed by a decrease in SF values in both dam models. This decline occurs gradually and cumulatively, indicating the accumulation of deformation and shear strain in the backfill material due to longer cyclic loads. This phenomenon is in line with the basic concept of soil behavior under dynamic loading, where the longer the load is applied, the greater the potential for degradation of soil shear strength.

At a relatively short duration of earthquakes, the dam response is still dominated by the initial elastic-plastic behavior of the material, so that the SF value obtained is relatively higher and stable. However, as the duration of the earthquake increases, the earthquake energy acting repeatedly causes an increase in permanent deformation, especially in material zones with lower rigidity and density. This condition contributes to a reduction in effective shear capacity and lowers the overall SF value.

A comparison of the results of the analysis between Model 1 and Model 2 shows that the effect of earthquake duration on the decrease in SF value is not uniform, but is strongly influenced by the configuration of materials and the zoning of the stockpile. Model 1, with a more complex zone division and more heterogeneous material variations, tends to show a decrease in SF values that are more sensitive to increased earthquake duration. This is due to differences in mechanical characteristics between zones that trigger stress redistribution and strain concentrations in potential slip fields.

Overall, the results of this discussion confirm that the duration of the earthquake is an important factor that can worsen the stability condition of the dam, even at the same magnitude of the earthquake. These findings reinforce the argument that the evaluation of dam safety in earthquake-prone areas should not only rely on a pseudo-static approach based on earthquake coefficients, but also consider the characteristics of the duration of the shock as part of the stability analysis.

The implication of this result is the need for caution in the selection of the configuration of the reservoir material and the zoning design of the dam, especially for the Urugan dam in areas with the potential for long-duration earthquakes. Dam models with more homogeneous materials and relatively high rigidity have been proven to provide better stability performance in the face of long-duration earthquake loads.

This subchapter comprehensively discusses the stability behavior of the urugan dam based on the results of PLAXIS numerical analysis for two material models (Model 1 and Model 2) on various water table and earthquake conditions. The discussion was carried out by relating the results of Safety Factor (ΣMsf) in static conditions, OBE earthquakes, and large earthquakes of 7.5 SR to the characteristics of the reservoir material, hydrostatic conditions, and the dynamic response of the dam body to seismic loading. Evaluation of applicable stability

standards is also included to ensure that the design meets international (ICOLD, USBR) and national (SNI 8460:2017) safety requirements.

This additional analysis was carried out as a follow-up to the seismic evaluation based on historical data on earthquake occurrences in the study area over ± 200 years. From these historical data, an empirical relationship between earthquake magnitude and shock duration was obtained through linear regression analysis, which resulted in a representative variation in earthquake duration for magnitude 7.5 SR. This duration variation is further used as an additional parameter in numerical stability analysis using PLAXIS at Normal Water Level (NWL) water level conditions.

Analysis of Construction Costs of Landfill Materials

This subchapter discusses the construction cost aspects of two alternative dam embankment material designs, namely Model 1 which uses a combination of sand-gravel material on the upstream side and sandstone on the downstream side, and Model 2 which uses sandstone material on both sides of the upstream and downstream slopes. This cost analysis was carried out to evaluate the influence of landfill material variations on the total dam construction cost, as well as provide a decision-making basis in selecting a material design that not only meets the criteria of stability, but is also economically effective.

This cost analysis utilizes a list of work quantities (Bill of Quantity/BOQ) and unit prices of materials, tools, and labor that apply to the latest RAB calculation standards. Each reservoir zone is calculated in volume based on the geometry of the dam design, then multiplied by the unit price of materials and implementation costs according to the components of the work item. The results of the cost analysis were then compared between the two models to determine the construction cost efficiency of each alternative.

The calculation of the volume of backfill materials is a fundamental step in determining the material needs in each dam zone and is the basis for calculating construction costs in the next subchapter. In this study, the volume of the reservoir was calculated based on the dam geometry model that had been modeled in the PLAXIS software and adjusted to the division of different zones in each design alternative (Model 1 and Model 2). The geometric output from PLAXIS is then extracted into the actual volume form using the cut-fill volume extraction method.

Integration of Stability Aspects and Cost Aspects

This subchapter integrates two main aspects used in the study, namely (1) dam stability based on the results of PLAXIS numerical analysis, and (2) construction cost aspects based on RAB Modeling 1 and Modeling 2. This integration is necessary to assess a design that is not only geotechnically safe, but also economically efficient, as these two aspects are often key considerations in the planning of an urugan dam.

The difference in material zone configuration between Modeling 1 and Modeling 2 results in variations in the safety factor (SF) value as well as the total cost of the material. Therefore, the selection of the best model cannot be determined based solely on one aspect, but must consider the trade-off of the balance between stability and cost, the efficiency of material use, and the choice of alternative materials capable of providing optimal performance.

CONCLUSION

This study evaluates how variations in embankment (stockpile) materials and water levels affect the stability of an urugan (earthfill) dam using PLAXIS, while also assessing economic implications through the RAB (Rencana Anggaran Biaya). The results indicate that material configuration significantly influences the Safety Factor (SF), with Modeling 1—featuring more complete zoning, including a coarse filter (Zone 2b) and separated sand–gravel materials—consistently producing higher SF values, better permeability, and improved drainage performance, particularly under a 7.5 SR earthquake. In contrast, Modeling 2, although more cost-efficient (saving Rp 7.98 billion or 1.41%), showed lower stability, especially under high water levels (FWL) and seismic loading. Increasing water levels from LWL to FWL reduced SF, increased pore water pressure, and raised driving forces in both models, though still within safe limits, with Modeling 1 demonstrating more resilience. Earthquake analyses (OBE and 7.5 SR) further reduced SF, with duration proving to be a critical factor; Modeling 1 exhibited better adaptability due to faster pore pressure dissipation. Overall, zoning configuration of embankment materials was the most dominant factor affecting dam stability compared to water level and seismic load variations, highlighting the need to balance technical safety and cost efficiency in design decisions. Future research is recommended to incorporate three-dimensional numerical modeling, real-time monitoring data, and probabilistic risk analysis to better capture complex field conditions and uncertainties, particularly under extreme climate and seismic scenarios.

REFERENCES

- Bedon, C., Zhang, X., Santos, F., Honfi, D., Kozłowski, M., Arrigoni, M., Figuli, L., & Lange, D. (2018). Performance of structural glass facades under extreme loads—Design methods, existing research, current issues and trends. *Construction and Building Materials*, *163*, 921–937.
- Bock, F. E., Aydin, R. C., Cyron, C. J., Huber, N., Kalidindi, S. R., & Klusemann, B. (2019). A review of the application of machine learning and data mining approaches in continuum materials mechanics. *Frontiers in Materials*, *6*, 110.
- Costa, A., Caldas, J. C., Coelho, R., Ferreira, M. de F., & Gonçalves, V. (2016). The building of a dam: Value conflicts in public decision-making. *Environmental Values*, *25*(2), 215–234.
- Digna, R. F., Mohamed, Y. A., van der Zaag, P., Uhlenbrook, S., van der Krogt, W., & Corzo, G. (2018). Impact of water resources development on water availability for hydropower production and irrigated agriculture of the Eastern Nile Basin. *Journal of Water Resources Planning and Management*, *144*(5), 5018007.
- Dillon, A., & Fishman, R. (2019). Dams: Effects of hydrological infrastructure on development. *Annual Review of Resource Economics*, *11*(1), 125–148.
- Gordan, B., Raja, M. A., Armaghani, D. J., & Adnan, A. (2022). Review on dynamic behaviour of earth dam and embankment during an earthquake. *Geotechnical and Geological Engineering*, *40*(1), 3–33.
- Jayanti, M., Marganingrum, D., Santoso, H., Qadafi, M., Mariana, M., Ariesyady, H. D., Sabar, A., Citraresmini, A., & Bachtiar, T. (n.d.). Using Rainfall Characteristics for Sustainable Water Resources Management in Monsoon Climate Zone. Available at SSRN 4949163.
- Kim, H. Y., Shin, C., Park, Y., & Moon, J. (2018). *Water resources management in the Republic of Korea: Korea's challenge to flood & drought with multi-purpose dam and*

multi-regional water supply system.

- Li, F., Zhang, P., Li, Q., Shen, Z., & Du, X. (2024). Decision-making study on risk evaluation of earth and rock dams based on ANP unascertained measurement theory. *Natural Hazards*, *120*(2), 1715–1753.
- Lin, P., Huang, B., Li, Q., & Wang, R. (2015). Hazard and seismic reinforcement analysis for typical large dams following the Wenchuan earthquake. *Engineering Geology*, *194*, 86–97.
- Luo, P., Mu, Y., Wang, S., Zhu, W., Mishra, B. K., Huo, A., Zhou, M., Lyu, J., Hu, M., & Duan, W. (2022). Exploring sustainable solutions for the water environment in Chinese and Southeast Asian cities. *Ambio*, *51*(5), 1199–1218.
- Mneina, A., & Shalaby, A. (2020). Relating gradation parameters to mechanical and drainage performance of unbound granular materials. *Transportation Geotechnics*, *23*, 100315.
- Paik, J. K. (2019). *Advanced structural safety studies: with extreme conditions and accidents*. Springer.
- Rejekiingrum, P., Apriyana, Y., Sutardi, Estiningtyas, W., Sosiawan, H., Susilawati, H. L., Hervani, A., & Alifia, A. D. (2022). Optimising water management in drylands to increase crop productivity and anticipate climate change in Indonesia. *Sustainability*, *14*(18), 11672.
- Salamah, E., El-Hasan, T., & Abu-Jamah, M. (2023). Dam safety in Jordan: Factors affecting dam safety, responsibilities and required actions. *Engineering*, *15*(9), 514–532.
- Seifi, M., Gorelik, M., Waller, J., Hrabe, N., Shamsaei, N., Daniewicz, S., & Lewandowski, J. J. (2017). Progress towards metal additive manufacturing standardization to support qualification and certification. *Jom*, *69*(3), 439–455.
- Travush, V., Emelianov, S., Kolchunov, V., & Bulgakov, A. (2016). Mechanical safety and survivability of buildings and building structures under different loading types and impacts. *Procedia Engineering*, *164*, 416–424.
- Wang, B., Zhong, S., Lee, T.-L., Fancey, K. S., & Mi, J. (2020). Non-destructive testing and evaluation of composite materials/structures: A state-of-the-art review. *Advances in Mechanical Engineering*, *12*(4), 1687814020913761.
- Wieland, M. (2016). Safety aspects of sustainable storage dams and earthquake safety of existing dams. *Engineering*, *2*(3), 325–331.
- Zhi, M., Zhu, Y., Jang, J.-C., Wang, S., Chiang, P.-C., Su, C., Liang, S., Li, Y., & Yuan, Y. (2023). Analysis of storage capacity change and dam failure risk for tailings ponds using WebGIS-based UAV 3D image. *Sustainability*, *15*(19), 14062.
- Zhou, C., Shen, Z., Xu, L., Sun, Y., Zhang, W., Zhang, H., & Peng, J. (2023). Global sensitivity analysis method for embankment dam slope stability considering seepage–stress coupling under changing reservoir water levels. *Mathematics*, *11*(13), 2836.