



Correlation of Permeability and Thickness of the Clay Core Zone on Plastic Deformation in the Melawi Dry Dam, Indonesia

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Abstract: The Melawi Dry Dam is a zoned embankment dam with clay core located in West Kalimantan, Indonesia. As a flood-control structure, it undergoes significant wet-dry cycles that modify stress distribution and pore water pressure, potentially influencing plastic deformation within the core zone. This study aims to evaluate the effects of clay core thickness and permeability coefficient on vertical plastic deformation using a combination of fully coupled flow-deformation and plastic analysis in PLAXIS 2D. Numerical simulations represent a post-flood condition followed by a 130-day consecutive dry season period, defined as Julian days when rainfall remains at the lower rainfall-gradient threshold, during which the reservoir remains empty because inflow exceeds outlet capacity. Nine scenarios were analyzed by combining three core thicknesses (11.64, 19.40, and 27.16 m) with three laboratory-determined permeability coefficients. The results indicate that seven scenarios remain below the maximum allowable deformation limit of 1.0% of the dam height. Statistical analysis shows a strong correlation between core thickness, permeability, and deformation ($R = 0.929$). Multiple linear regression (Significance $F = 0.00253$; $p < 0.05$) confirms that both variables significantly affect deformation. Increasing core thickness consistently reduces plastic deformation, while lower permeability enhances resistance to seepage-induced instability, thereby supporting safe dry dam design.

Keywords: Clay core thickness; Dry dam; Fully coupled analysis; Permeability coefficient; Plastic deformation

Introduction

One type of dam that is suitable for regions experiencing high discharge fluctuations is a dry dam, which functions as a flood control structure with a reservoir that is only impounded during the rainy season and remains dry during the dry season (Malindo et al., 2023). Comprehensive safety standards and risk management frameworks are essential for all dam types, including dry detention dams and permanent reservoir dams (Mayangsari et al., 2025; Federal Emergency Management Agency, 2005). Therefore, dry dams still require comprehensive technical evaluations, particularly with respect to structural stability, seepage conditions, and reduce shear strength, under the influence of extreme wet-dry cycles (Barurrokhim et al.,

2022; Wang et al., 2018; Texas Commission on Environmental Quality, 2009).

Unlike permanent dams, dry dams experience more significant transitions between saturated and unsaturated conditions because water is stored only temporarily during flood events (Malindo et al., 2023). During the dry season, inflow discharge does not exceed the capacity of the bottom outlet, allowing all incoming flow to be directly released downstream, which results in an unimpounded reservoir condition. Under these circumstances, the dam body, particularly the clay core zone, tends to remain in an unsaturated state for a relatively extended period (Liu et al., 2024). In contrast, during the rainy season, although water is continuously discharged downstream through the outlet works, inflow frequently exceeds the bottom outlet capacity, causing the reservoir to fill and a temporary water

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column to form within the dam body (Li et al., 2019). This operational pattern subjects the dam to repeated and more extreme wetting–drying cycles compared to permanent reservoir dams.

During prolonged dry periods, the absence of a permanent water column may trigger drying processes and the formation of desiccation cracks within the clay core zone (Shafqat et al., 2025). Luo et al. (2023) explained that desiccation cracking can modify effective permeability, alter seepage paths, and influence the mechanical behavior of clay, where stiffness may increase under dry conditions while long-term shear strength decreases due to repeated wet–dry cycles (Wardani et al., 2017). These material property changes may potentially increase plastic deformation within the core zone (Putri et al., 2025b).

Plastic deformation is closely related to stress–strain distribution, which is influenced by variations in pore water pressure resulting from seepage processes (Liu et al., 2014; Levatti, 2022). The magnitude of seepage is primarily governed by the permeability coefficient and the length of the seepage flow path (Al-Janabi et al., 2020; Koschwitz et al., 2023). Increasing core thickness extends the seepage path, reduces hydraulic gradients, and lowers the phreatic surface, thereby potentially improving hydraulic performance and deformation control (Kawy et al., 2021).

The Melawi Dam in West Kalimantan is planned as a dry dam with a clay core, operating only when inflow exceeds outlet capacity, which causes annual fluctuations between saturated and unsaturated conditions. However, studies integrating permeability

variation and core thickness effects on plastic deformation under the characteristic wet–dry cycles of dry dams remain limited. This study analyzes these effects using fully coupled flow–deformation and plastic analysis in PLAXIS 2D. The novelty of this research lies in integrating hydro-mechanical numerical modeling with statistical evaluation to quantify the combined effects of hydraulic and geometric core parameters under representative dry dam operational conditions, thereby providing a more rational basis for optimizing clay core design.

Method

Study Area and Data

The study was conducted at the Melawi Dry Dam site, located on the Pinoh River in Melawi Regency, West Kalimantan Province, Indonesia. The dam is situated approximately 39 km upstream of Nanga Pinoh City and has a structural height of 43 m measured from the riverbed. Geographically, the site is located at 0°35'23.19" S and 111°44'49.54" E.

The Melawi Dry Dam is designed to mitigate flooding associated with the 20-year flood discharge in Sintang Regency. Flooding in this region is primarily attributed to the limited channel capacity at the confluence of the Kapuas Hulu and Melawi rivers, which is unable to convey the cumulative flow from both rivers. Based on the current hydrological analysis, the combined peak discharge reaches 10,915 m³/s, corresponding to an estimated return period of approximately 1.59 years.

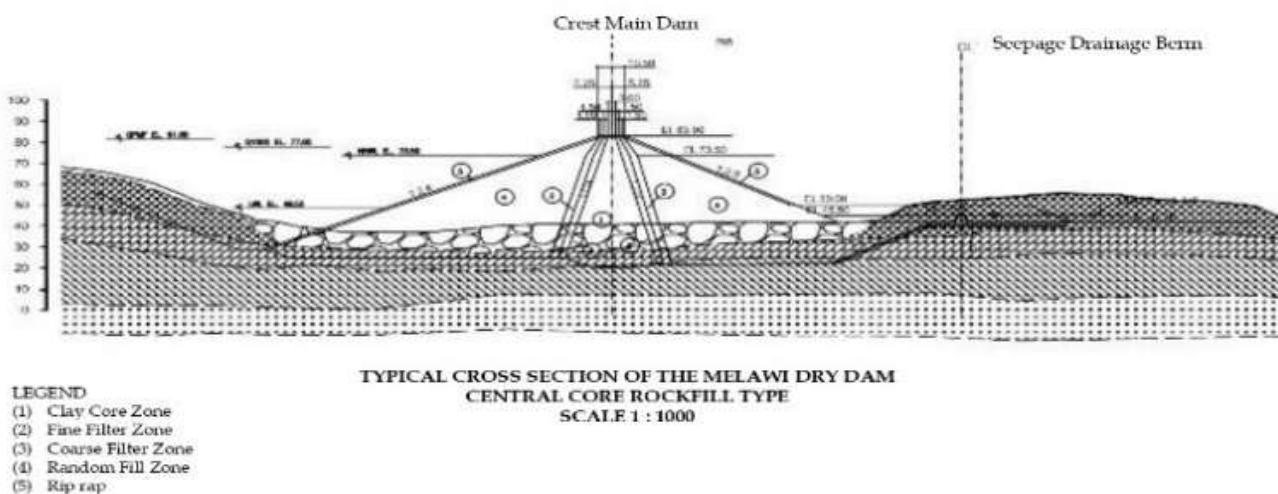


Figure 1. Cross section of Melawi dry dam

The Melawi Dry Dam has a total storage capacity of 1,202.85 million m³ with a maximum inundation area of 11,239.71 hectares, with the riverbed elevation at 40.0 m. Furthermore, the reservoir is considered empty when the dam conveys normal river discharge (baseflow),

representing conditions equivalent to the pre-dam state. Under this condition, the baseflow discharge is 495.89 m³/s, with a corresponding water level elevation of 48.50 m. This baseflow is released downstream through an ungated bottom outlet.

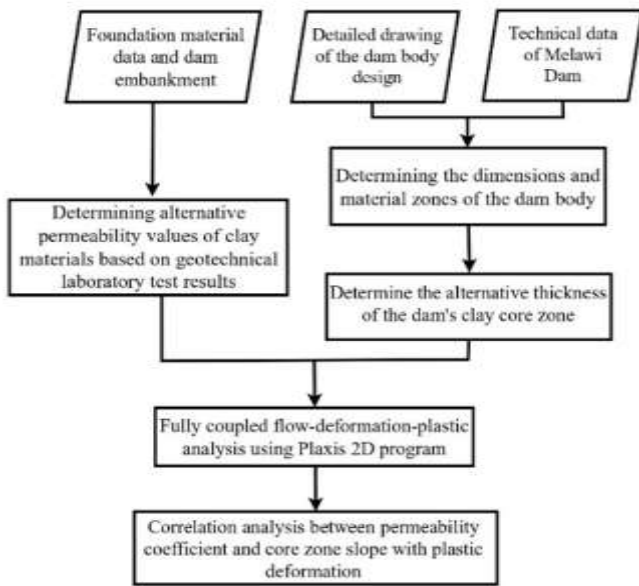


Figure 2. Research flow diagram

Water Level Fluctuation Scenario for Deformation Analysis

In the deformation analysis of the Melawi Dry Dam, the reservoir operation pattern must be carefully considered, as it differs fundamentally from that of a multipurpose dam. The operation of the Melawi Dry Dam is strongly governed by the duration of the rainy

and dry seasons, which determines the period during which the dam body remains in saturated and dry conditions, respectively. Based on the analysis of daily rainfall data recorded at the Nanga Pinoh rainfall station from 2003 to 2022 using a fifth-order polynomial method, the dry-season duration within the Melawi Dry Dam catchment area was estimated to be 130 days.

In addition, due to its natural operation without gated outlets, the Melawi Dry Dam experiences gradual water level recession following flood events as water is released downstream. Based on flood routing analysis through the bottom outlet, which has a diameter of 7.5 m and a discharge capacity of 1,000 m³/s, the duration of water level drawdown from the 20-year flood water level (El. +77.5 m) to the low water level (El. +48.5 m) was estimated to be 16 days, under conditions where the inflow had returned to normal baseflow at 495.89 m³/s.

During this period, the reservoir discharge remained below the maximum capacity of the bottom outlet, so the dam remained unimpounded. Considering the operational characteristics of the Melawi Dry Dam, the plastic deformation analysis was conducted by simulating the dry-season operation over a total duration of 130 days. Therefore, this analysis was performed using a slow drawdown approach, in which the water level changes gradually to allow sufficient dissipation of pore water pressure within the clay core.

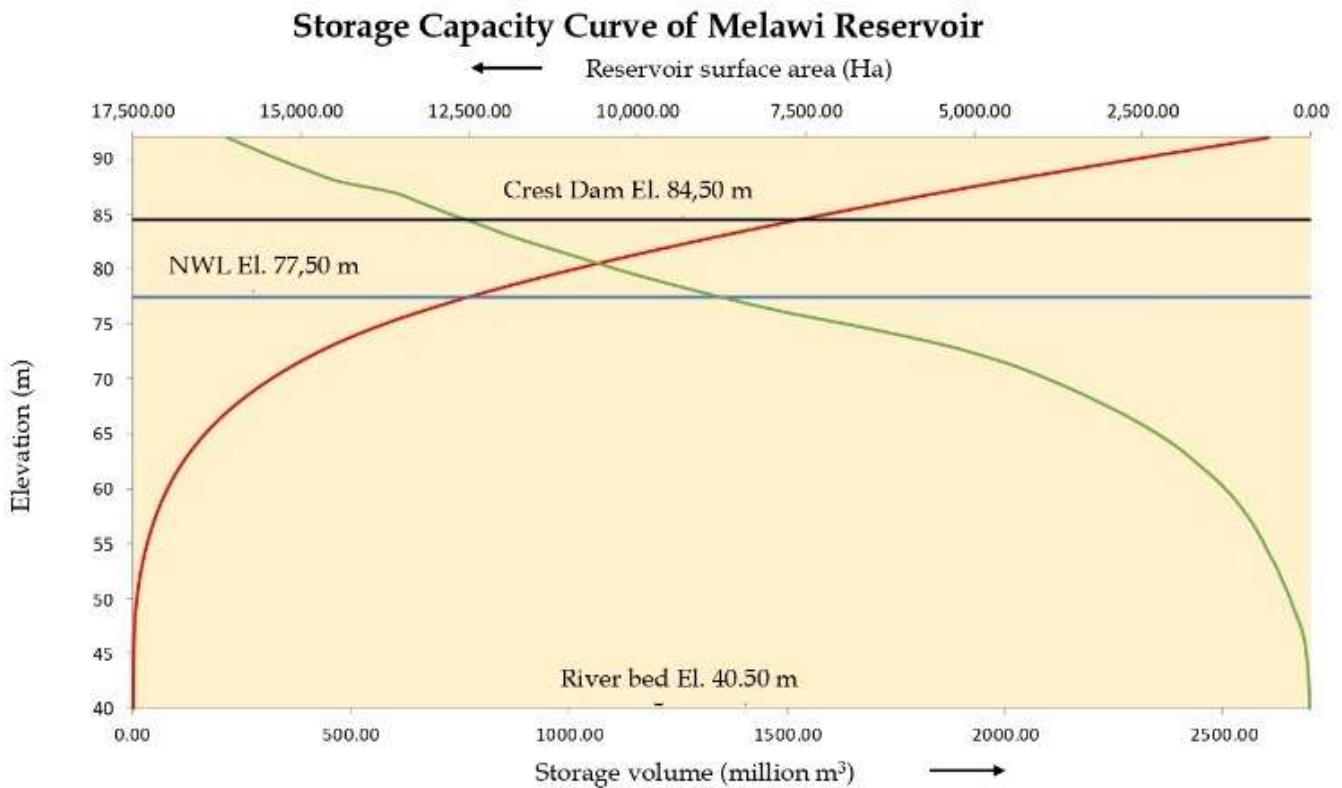


Figure 3. Storage capacity of Melawi reservoir

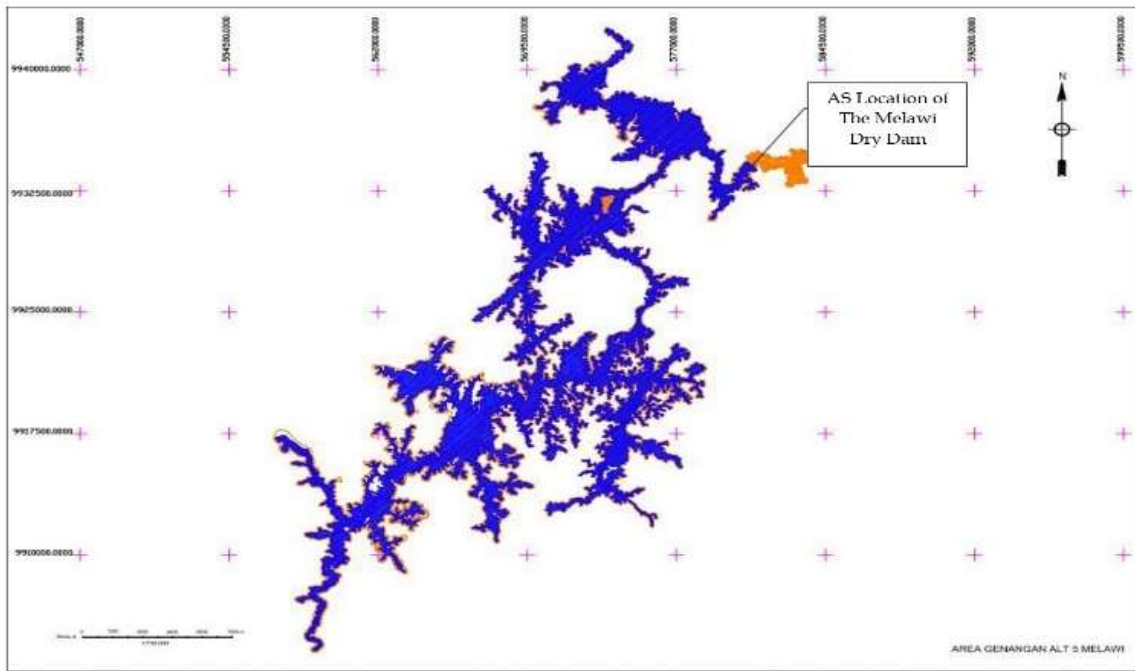


Figure 4. Inundation map of the Melawi dry dam

Core Zone Thickness Design Criteria

The average thickness of the impermeable zone in embankment dams ranges from approximately 30% to 50% of the water height (Pusat Pengembangan Kompetensi SDA & Permukiman, 2021).

Coupled Flow-Deformation Analysis Using Plaxis 2D

The fully coupled flow-deformation analyses phase calculated the change in DoS, effective vertical stress, and confining pressure with time and continuously updated the stress-strain model and deformations simultaneously (Ravichandran et al., 2021). Once the simulation was complete, the deformations, DoS, and suction were measured. This distinction transformation during the fully coupled deformation analyses is shown in Equation (1).

$$\begin{aligned} \sigma' &= \sigma - P_a + \chi (P_a - P_w) \\ \sigma' &= \sigma - S_{eff} \times (P_{steady} - P_{excess}) \\ \sigma' &= \sigma - P_{active} \end{aligned} \tag{1}$$

Where σ is the total stress, P_a is atmospheric pressure, P_w is pure water pressure (P_w), and χ is the suction coefficient. PLAXIS 2D assumes P_a to be zero and χ is set equal to the effective saturation.

The transformed equation relies on the effective saturation (S_{eff} Equation (2)), steady-state pore water pressure (P_{steady}) and excess pore water pressure (P_{excess}) to define the active pore water pressure (P_{active}).

$$S_{eff} = \frac{S - S_{res}}{S_{sat} - S_{res}} \tag{2}$$

Where S_{res} is the residual DoS and S_{sat} is the saturated DoS.

The coupled finite element equation implemented in PLAXIS 2D for capturing the deformation of the soil body as expressed in standard solid mechanics notations is shown Equation (3).

$$\begin{bmatrix} \underline{\underline{K}} & \underline{\underline{Q}} \\ \underline{\underline{C}} & \underline{\underline{-S}} \end{bmatrix} \begin{bmatrix} \frac{d\underline{\underline{v}}}{dt} \\ \frac{d\underline{\underline{p_w}}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \underline{\underline{H}} \end{bmatrix} \begin{bmatrix} \underline{\underline{v}} \\ \underline{\underline{p_w}} \end{bmatrix} = \begin{bmatrix} \frac{d\underline{\underline{f_u}}}{dt} \\ \underline{\underline{G}} + \underline{\underline{q_p}} \end{bmatrix} \tag{3}$$

where $\underline{\underline{K}}$ is the stiffness matrix, $\underline{\underline{v}}$ is the nodal values of the displacements, $\underline{\underline{Q}}$ is the coupling matrix, $\underline{\underline{p_w}}$ is the pore water pressure, $d\underline{\underline{f_u}}$ is the increment of the load vector, is the $\underline{\underline{H}}$ is the permeability matrix, $\underline{\underline{G}}$ is a vector in which effect of gravity on flow in the vertical direction is considered, $\underline{\underline{q_p}}$ is the flux on boundaries, $\underline{\underline{C}}$ is the coupling matrix, and $\underline{\underline{-S}}$ is the compressibility matrix.

This integrated formulation allows changes in pore pressure to influence effective stress and deformation directly, while deformation alters soil permeability and flow paths, leading to a fully interactive response. Such coupling is especially important for transient problems involving rapid water level changes, seepage forces, or consolidation, where uncoupled approaches may fail to capture the essential hydro-mechanical feedbacks (He et al., 2016; Zhao et al., 2024; Zheng et al., 2024).

Deformation Acceptance Criteria for Rockfill Dams

ICOLD emphasizes that permanent deformations must remain within limits that do not compromise the

freeboard, slope stability, or the integrity of auxiliary structures. Although the original context pertains to the post-construction period, the underlying principle applied is the control of total deformation to ensure the safety of the dam throughout its service life (ICOLD, 1993). The vertical deformation of rockfill dams can be evaluated using acceptance criteria derived from previous studies, as presented in Table 1.

Table 1. Settlement acceptance criteria for rockfill dams

Reference	Deformation Parameters	Deformation Threshold (% of Dam Height)
ICOLD (1993)	Crest	0.2-1.0
	Slope	0.1-0.2
Sowers (1965)	Crest	0.25-1.0
Sherard et al. (1963)	Crest	0.1-0.4

Multiple Correlation

This analysis aims to quantify the strength and degree of relationship among three variables, namely X1 (the core zone thickness), X2 (the permeability coefficient), and Y (deformation).

$$R_{yx_1x_2} = \sqrt{\frac{r^2_{x_1Y} + r^2_{x_2Y} - 2 \cdot r_{x_1Y} \cdot r_{x_2Y} \cdot r_{x_1x_2}}{1 - r^2_{x_1x_2}}} \quad (4)$$

Where r is the correlation coefficient between variables X1 with Y, r_{x_2Y} adalah is the correlation coefficient between variables X1 with Y, and $r_{x_1x_2}$ is the correlation coefficient between variables X1 dan X2. After obtaining the coefficient of multiple correlation (R), the strength of the relationships among the variables can be determined (Sugiyono, 2010), as presented in Table 2.

Table 2. Strength of relationship based on the correlation coefficient

Correlation Coefficient Interval	Strength of Relationship
0-0.2	Very weak
0.2-0.4	Weak but definite
0.4-0.7	Moderate
0.7-0.9	Very strong
0.9-1.0	Extremely strong

Multiple Linear Regression

This method aims to evaluate the simultaneous effect of multiple predictors on a single outcome variable and to estimate or predict the dependent variable based on the combined influence of the independent variables (Adhikari, 2022).

$$Y = a + b_1X_1 + b_2X_2 \quad (4)$$

where Y is the dependent variable, X1, X2, ..., Xn are the independent variables, a is the intercept, b represents the regression coefficients indicating the magnitude and direction of each independent variable's effect.

Result and Discussion

Deformation Analysis of the Melawi Dry Dam

In the plastic deformation analysis of the Dry Dam, three alternative permeability coefficients of clay were adopted based on the results of geotechnical laboratory testing. By combining these two design parameters, a total of nine numerical scenarios were developed for the deformation analysis of the Melawi Dry Dam. The analyses were performed using PLAXIS 2D to simulate the coupled mechanical response of the embankment under the prescribed conditions. The resulting deformation characteristics for each scenario are presented and comparatively evaluated in Table 3.

As presented in Table 3, the plastic deformation analysis using PLAXIS 2D for nine variations of clay core thickness and permeability coefficient shows that most cases satisfy the ICOLD deformation safety criteria of 0.2-1.0% of the dam height. Considering a dam height of 43 m, the allowable deformation range for the Melawi dry dam is between 0.086 m and 0.43 m, in accordance with the established safety criteria. Three clay core thicknesses were evaluated, namely 11.64, 19.4, and 27.16 m, under different permeability values. The results indicate that seven out of nine cases fall within the allowable deformation range. However, two cases with a clay core thickness of 11.64 m exceed the maximum permissible limit, reaching deformation values of 0.454 m and 0.522 m.

In soil mechanics analysis, plastic deformation in saturated soils is strongly governed by changes in effective stress, which is controlled by pore water pressure. According to the effective stress principle introduced by Terzaghi (1925), the effective stress (σ') is defined as the difference between total stress (σ) and pore water pressure (u), meaning that any variation in pore water pressure directly influences the bearing capacity and deformation behavior of the soil. When soil has low permeability, the rate of pore water pressure dissipation becomes very slow. As a result, excess pore water pressure remains high for a longer period, causing the effective stress to stay low during an extended drainage phase. Consequently, the soil becomes more susceptible to significant plastic strain because its shear strength decreases and the soil skeleton behaves under nearly undrained conditions, which promotes the accumulation of permanent deformation (Głuchowski & Sas, 2020).

In the context of cyclic loading conditions such as rapid drawdown or reservoir water level fluctuations, excess pore water pressure trapped within low-permeability soils does not dissipate quickly when the load changes rapidly. This phenomenon prolongs the period during which the soil remains in an undrained condition, leading to a greater reduction in effective

stress and consequently increased plasticity. Experimental studies have shown that excess pore water pressure generated by cyclic loading or repeated load variations correlates with the accumulation of plastic

strain; when pore water pressure does not dissipate rapidly, plastic strain accumulates more quickly and to a greater extent compared to conditions where drainage occurs more easily (Głuchowski & Sas, 2020).

Table 3. Deformation analysis of the Melawi dry dam

Thickness of Clay Core (m)	Permeability Coefficient of Clay Soil (m/day)	Deformation Vertical (m)	ICOLD Criteria for Deformation Safety (0.086–0.43 m)
11.64	2.81E-02	0.381	Meets the Criteria
11.64	4.50E-04	0.454	Does Not Meet the Criteria
11.64	7.66E-06	0.522	Does Not Meet the Criteria
19.4	2.81E-02	0.315	Meets the Criteria
19.4	4.50E-04	0.363	Meets the Criteria
19.4	7.66E-06	0.401	Meets the Criteria
27.16	2.81E-02	0.250	Meets the Criteria
27.16	4.50E-04	0.359	Meets the Criteria
27.16	7.66E-06	0.388	Meets the Criteria

The distribution and rate of dissipation of excess pore water pressure play a crucial role in controlling the settlement pattern and the potential for lateral deformation in soft soils. When excess pore water pressure remains high over an extended period, the effective stress stays low, preventing the soil skeleton from carrying the applied load efficiently. As consolidation progresses and pore water pressure gradually dissipates, the effective stress correspondingly increases. However, this process is often accompanied by significant accumulation of permanent strain. In some cases, non-uniform dissipation of pore water pressure may also trigger differential movements and stress redistribution within the soil mass, further amplifying plastic deformation (Tama et al., 2013; Sukiman, 2017).

Furthermore, although a low permeability value may indicate safety against excessive plastic deformation, the hydraulic behavior of the soil must still be carefully evaluated in relation to seepage and piping

hazards (Putra, 2022; Rasinan et. al., 2024). High permeability implies that water can move more easily through soil pores, thereby increasing the seepage rate. From a geotechnical perspective, soils with high permeability tend to dissipate excess pore water pressure more rapidly and are therefore relatively safer against the accumulation of transient pore pressure (Rasinan et. al., 2024). However, this condition does not necessarily guarantee overall stability. One of the primary consequences of high permeability is the increased potential for seepage and piping, which refer to the transport of soil particles by flowing water and may lead to internal erosion within the soil structure (Baskara et al., 2023). An increase in permeability is often correlated with a higher likelihood of piping, as faster seepage flow enables the seepage force to mobilize soil particles, resulting in the development of flow channels within the soil mass and internal erosion when the hydraulic gradient exceeds its critical threshold (Arungtasik et al., 2024).

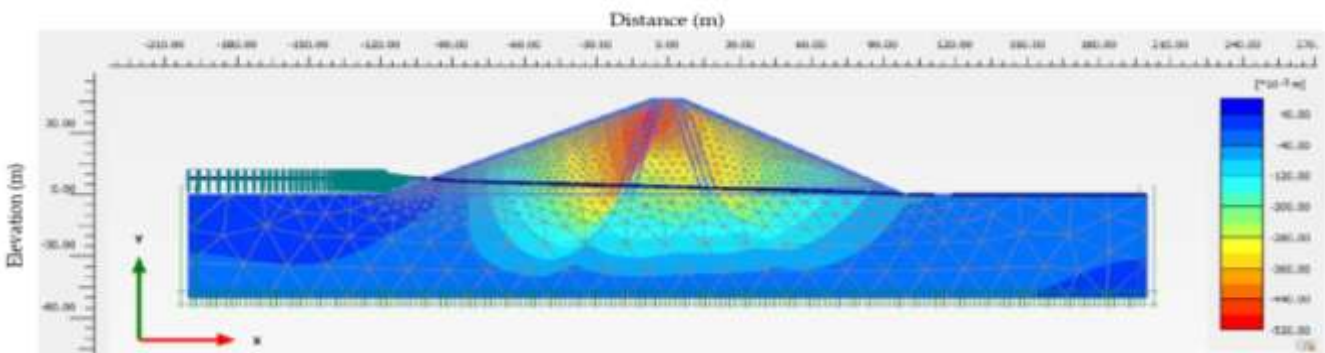


Figure 5. Plastic deformation analysis results of the Melawi dry dam

Figure 5 presents the deformation results of the Melawi dry dam under reservoir conditions adjusted to the wetting–drying cycles, indicating that plastic deformation tends to be more pronounced on the upstream side of the embankment. In earthfill or rockfill

dams, greater deformation on the upstream slope is primarily attributed to its direct interaction with reservoir water level fluctuations, which induce increases in pore water pressure and alter the effective stress distribution within the dam body. As the reservoir

level rises, the phreatic line correspondingly increases, leading to higher degrees of saturation in the upstream zone, a reduction in shear strength, and a more intensive consolidation process compared to the downstream side (Liu et al., 2024; Banerjee et al., 2023). Under rapid drawdown conditions, excess pore water pressure within the upstream slope cannot dissipate immediately, resulting in elevated hydraulic gradients and additional deformation before a new equilibrium state is achieved (Zhang et al., 2019; Zhao et al., 2024).

The observed behaviour can primarily be explained by the interaction among soil stiffness, stress redistribution, and permeability characteristics. A thinner clay core tends to undergo greater deformation due to its higher compressibility and reduced lateral confinement (Topçu & Seyrek, 2023). This condition leads to increased vertical settlement resulting from self-weight, seepage forces, and load transfer from the adjacent rockfill shells. This trend aligns with finite element studies that show deformation magnitude increases as core thickness decreases and soil stiffness lowers, which elevates pore pressures and plastic strain development near the impermeable core (Nowamooz, 2023; Pan et al., 2024).

Multiple Correlation Analysis

A multiple correlation analysis was conducted to quantitatively evaluate the combined influence of core zone thickness and clay permeability coefficient on the vertical deformation of the Melawi Dry Dam, considering that embankment dam deformation is often governed by multiple interacting physical factors. In structural deformation monitoring studies, correlation-based frameworks are widely applied to identify significant relationships between design or operational parameters and deformation responses, thereby improving the accuracy of predictive models and dam safety assessments (Shi et al., 2024).

Furthermore, multi-point modeling studies have demonstrated that incorporating correlations among parameters contributes to a more accurate understanding and prediction of deformation behaviour in geotechnical structures such as earth-rock dams (Pi et al., 2024). Empirical studies in Indonesia also emphasize the importance of analyzing interdependencies between design parameters and deformation in assessing embankment dam behaviour, including the relationship between core properties and overall deformation response (Kurniawan et al., 2021). Therefore, in this study, the multiple correlation coefficient (R) was calculated to assess the collective contribution of core thickness and permeability to the observed deformation of the Melawi Dry Dam, providing a basis for understanding deformation mechanisms and design recommendations.

Table 4. Correlation coefficient (R) from the simple correlation analysis

	Thickness (X ₁)	Permeability (X ₂)	Deformation (Y)
Thickness (X ₁)	1		
Permeability (X ₂)		1	
Deformation (Y)	0.673	0.641	1

Thickness (X₁) and Permeability (X₂) are controlled independent variables, designed such that no correlation exists between them. This ensures that the effects of each variable on the dependent variable can be evaluated separately, without confounding influence from the other (Fhonna et. al., 2025; Ruknan, 2025; Sastrawijaya, 2023). After the correlation coefficient (r) between two variables is determined, the correlation coefficient for three variables (R) is 0.929. The multiple correlation analysis was conducted to quantitatively evaluate the combined influence of core zone thickness and clay permeability coefficient on the vertical deformation of the Melawi Dry Dam. A correlation coefficient of 0.929 indicates a very strong relationship among these variables, supporting the technical expectation that both the thickness and permeability of the core significantly affect the deformation response.

This finding is consistent with the principles of fully coupled flow -deformation analysis, in which changes in pore water pressure, seepage forces, and stress redistribution interact to control plastic strain development within the core and surrounding shells (Bhutto et al., 2020; Siacara et al., 2025; Pan et al., 2024). Therefore, the multiple correlation approach is technically appropriate as it captures the interdependent effects of core design parameters on dam deformation, reflecting the physical mechanisms predicted by PLAXIS 2D plastic deformation simulations. The results highlight the importance of considering both hydraulic and mechanical properties in embankment dam design and provide empirical support for parameter optimization to ensure structural safety (Deng et al., 2025; Kurniawan et al., 2021).

Multiple Linear Regression Analysis

The Multiple Linear Regression (MLR) approach to providing rigorous evaluation of predictive relationships between thickness, permeability, and deformation responses under operational and hydraulic loading. The application of regression models for deformation prediction has been widely documented in civil and structural engineering research literature as an effective statistical tool for identifying key predictors in structural behavior analysis (Shi et al., 2024; Kurniawan et al., 2023; Nasution et al., 2023). In multiple linear regression, ANOVA compares the variance explained by the model with the residual (error) variance, and the F-

statistic is used to test whether at least one independent variable makes a statistically significant contribution to the observed variation in deformation (Putri et al., 2025a; Kurniawan et al., 2023; Siburian & Mardiyanti, 2023; Sureiman & Mangera, 2020).

Table 5. Overall F-test in the ANOVA of the multiple linear regression model

	df	SS	MS	F	Significance F
Regression	2	0.04383	0.02191	31.551	0.000655
Residual	6	0.00417	0.000696		
Total	8	0.04799			

Table 6. Partial t-test in the multiple linear regression model

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.41831	0.03473981	12.04134866	0.00001991
Thickness of Clay Core	-0.00775	0.00138651	-5.59188068	0.00139
Permeability Coefficient of Clay Soil	-0.03406	0.00603745	-5.64206236	0.00133

In Table 5 and Table 6, the significant F-value and p-values from the analysis of variance (ANOVA) are presented. Based on Table 5, the significance value of the F-test is 0.000655. When compared with the predetermined significance level ($\alpha = 0.05$), this value is smaller than 0.05; therefore, the null hypothesis (H_0) is rejected and the alternative hypothesis (H_1) is accepted (Lestari & Lidyasari, 2024). This result indicates that, simultaneously, the core zone thickness (X_1) and the permeability coefficient (X_2) have a statistically significant effect on deformation (Y). Furthermore, the partial test results (t-test) shown in Table 6 reveal that the p-value for core zone thickness (X_1) is 0.00139 and for the permeability coefficient (X_2) is 0.00133. Since both values are less than $\alpha = 0.05$, each independent variable individually has a significant effect on deformation.

Based on the regression coefficients presented in Table 6, the multiple linear regression equation can be expressed as $Y = 0.41831 - 0.00775X_1 - 0.03406X_2$. In linear regression analysis, the sign of each coefficient indicates the nature of the relationship between predictor and response variables; a negative coefficient suggests an inverse relationship, meaning that as the predictor increases, the response tends to decrease (Lestari & Lidyasari, 2024; Perdani et al., 2023; Hair et al., 2021; Hutcheson, 2017; Ijonu et al., 2024). The regression coefficients for core zone thickness (X_1) and permeability coefficient (X_2) are negative. These negative signs indicate an inverse relationship with deformation (Y). In other words, increasing the thickness of the core zone and increasing the permeability value of the clay material used in the core zone tend to reduce the magnitude of deformation. This finding is consistent with a geotechnical perspective, in which soils with high permeability tend to dissipate excess pore water pressure more rapidly and are therefore relatively safer against the accumulation of transient pore water pressure (Rasnan et al., 2024). However, in this analysis, the influence on seepage characteristics was not considered. One of the primary consequences of high permeability is the increased potential for seepage and piping, which refer to the transport of soil particles by

flowing water and may lead to internal erosion within the soil structure (Baskara et al., 2023).

Numerical analyses demonstrate that increasing core thickness extends the seepage path and reduces pore water pressure and flow discharge, thereby decreasing the hydraulic gradients that trigger deformation (Mostafa & Shen, 2023). Research on high core rockfill dams also indicates that controlling the permeability coefficient of core materials contributes to stabilizing seepage characteristics and reducing internal deformation responses (Guo, 2025). Theoretically, a thicker core with controlled permeability reduces flow intensity and soil stress changes, thereby lowering deformation potential (Anggraini & Haris, 2025). Optimizing permeability and core configuration is directly associated with reduced seepage discharge and improved structural stability (Kamiruddin et al., 2022).

Conclusion

The results of the numerical analysis using PLAXIS 2D and a statistical approach indicate that the core zone thickness and the permeability coefficient of the clay material significantly influence the vertical plastic deformation of the Melawi Dry Dam. Out of nine design variations of core thickness and permeability, seven configurations satisfy the deformation acceptance criteria of the International Commission on Large Dams (ICOLD). Deformation exceeding the allowable limit occurs only in the configuration with the smallest core thickness (11.64 m) combined with low permeability values (4.50×10^{-4} and 7.66×10^{-6}), indicating that the deformation response is governed by the interaction between geometric and hydraulic parameters rather than by a single parameter alone. The correlation analysis ($R = 0.929$) and multiple linear regression results (Significance F = 0.00253; p-value < 0.05) confirm that both variables simultaneously and partially have a significant effect on deformation. Although the regression coefficients are negative, indicating an inverse tendency, this interpretation must be placed within the operational context of a dry dam. The

interpretation of the influence of core thickness and permeability on the resulting plastic deformation is limited to the deformation mechanism itself and does not consider the relationship with seepage performance. Although the regression equation yields negative coefficients for both variables, this inverse relationship must be interpreted within the operational context of a dry dam. In this system, excessively low permeability inhibits the dissipation of excess pore water pressure during drawdown conditions, prolonging undrained behavior and promoting plastic strain accumulation. Conversely, higher permeability facilitates faster pore pressure dissipation, reducing deformation during cyclic wet-dry operation. Nevertheless, permeability cannot be increased indiscriminately, as excessive permeability compromises the seepage control function of the core. Mechanically, increasing core thickness extends the seepage path and reduces hydraulic gradients, while permeability must be controlled to balance two competing requirements: seepage resistance and adequate pore pressure dissipation. Therefore, the stability of the dry dam under cyclic wet-dry operational conditions depends on achieving an optimal balance between core geometry and hydraulic conductivity, rather than maximizing or minimizing a single parameter.

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Author Contributions

Conceptualization, A.R.D.O. (lead) and A.W.W.S. (supporting); methodology, A.R.D.O. (lead) and A.P.H. (supporting); software, formal analysis, investigation, resources, data curation, writing original draft preparation, visualization, project administration, A.R.D.O.; validation, A.R.D.O., A.W.W.S., and A.P.H.; writing review and editing, A.W.W.S. and A.P.H.; supervision, A.W.W.S. (lead) and A.P.H. (supporting); funding acquisition, A.W.W.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or

interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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