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Vertical Deformation of Manikin Asphalt Concrete Core Dam Using Mohr-Coulomb and Hardening Soil Material Models with Plaxis 2D Software

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Abstract

The Manikin Dam, located in Taebenu District, Kupang Regency, East Nusa Tenggara Province, is currently under construction. The dam is designed with an asphalt concrete core. The initial foundation elevation of the Manikin Dam was set at 103 meters above sea level due to fluctuating NSPT values. Consequently, the Dam Safety Commission recommended lowering the foundation elevation to 98 meters above sea level. This study aims to analyze the relationship between vertical deformation and stability in the Manikin Dam design at different foundation elevations. The modeling was conducted using Plaxis 2D V22, simulating asphalt concrete with two material models: Mohr-coulomb and hardening soil. The analysis results indicate that as the embankment height increases at different foundation elevations, the safety factor decreases while vertical deformation increases. At the final stage of embankment construction, the vertical deformation of the Manikin Dam at a foundation elevation of 103 meters for the mohr-coulomb core material model is 35.12 cm with a safety factor of 1.723, whereas, for The hardening soil core material model, it is 35.74 cm with a safety factor of 1.720. At a foundation elevation of 98 meters, the vertical deformation is 35.81 cm for the mohr-coulomb core material model with a safety factor of 1.716 and 36.69 cm for The hardening soil core material model with a safety factor 1.724. The safety factor and vertical deformation values for the dam core using both the mohr-coulomb and hardening soil material models remain within permissible limits.

Keywords*:* Stability; Vertical Deformation; Mohr-coulomb; Hardening soil.

1. Introduction

The Manikin Dam was initially planned as a rockfill dam with a vertical clay core. However, further investigations were conducted to assess the material conditions. The borrow area in East Baumata, located 2 to 3 kilometers downstream of the main dam site, was explored for clay core material. The soil composition in this borrow area was heterogeneous, consisting of expansive Bobonaro clay and fragmented limestone blocks. The availability of clay material that meets technical specifications around the Manikin Dam construction site was insufficient, and the transportation distance to procure suitable clay from outside the construction area was considerable. Consequently, the Evaluation Team for Dam Construction and Management from the Ministry of Public Works and Housing (PUPR) recommended changing the dam core material from clay to asphalt concrete.

The initial supervision team planned the foundation at an elevation of 98 meters above sea level, by the foundation design outlined in the Manikin Dam design certification report. However, during the construction phase, foundation-bearing capacity tests (Feng et al., 2020) indicated suboptimal results for the Asphalt Core Dam design. At an elevation of 103 meters above sea level, the deformation modulus was recorded at 1136 kg/cm² with an NSPT value of 56 blows/ft, classifying the rock hardness as DM grade. Consequently, the Dam Safety Commission of the Ministry of Public Works and Housing recommended a redesign involving deeper foundation placement. The Manikin Dam was ultimately designed at the riverbed elevation of 98 meters above sea level, where the rock hardness was classified as CL grade, with a deformation modulus of 3300 kg/cm² and an NSPT value exceeding 60 blows/ft.

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The asphalt concrete core exhibits strong resistance to water pressure due to its high density and inherent strength. It is designed with an air void content of less than 3%, ensuring minimal permeability and preventing hydraulic fracturing (Zhang et al., 2015). Given the modification of the asphalt core design, further analysis is required, as the greatest dynamic amplification and acceleration typically occur at the upper section of the dam. The asphalt concrete core may experience shear stress and strain, which can lead to cracking (International Commission on Large Dams, 2018). Changes in the dam core height necessitate a reassessment of stability and vertical deformation to ensure that vertical deformation at each embankment increment remains within permissible limits. The modeling scenarios are based on asphalt concrete core embankment height increments at different foundation elevations using Plaxis 2D V22 software.

2.Materials and Method

2.1. Required Data

The Manikin Dam is located in Taebenu District, Kupang Regency. Geographically, it is positioned at coordinates 10º 12’ 46’’ S and 123º 43’ 04’’ E, as illustrated in Figure 1. The Manikin Dam is planned to serve multiple functions, including irrigating an area of approximately 401.297 hectares, supplying raw water at a rate of ±0.7 m³/s, generating 0.13 Megawatts of hydroelectric power (PLTMH), mitigating floods by 331 m³/s, and supporting tourism. The dam features an asphalt concrete core with a width of 90 cm, which complies with Norway’s standard for asphalt concrete cores, requiring a minimum width of 50 cm and a maximum of 100 cm (Hoeg K, 1993). A more conservative design criterion suggests that the asphalt concrete core width should be 1/10 of the dam height (International Commission on Large Dams, 2018). The asphalt concrete core was modeled in Plaxis 2D V22 using two material models Mohr-coulomb and hardening soil. A triaxial test was conducted on trial embankment samples of asphalt concrete, with sample extraction performed through drilling. The triaxial testing of the asphalt core samples was carried out at Sidan Dam, as asphalt triaxial testing requires specialized equipment. The triaxial tests were conducted using water at a temperature identical to that of the deepest section of the riverbed, set at 20°C. The test results provided values for deviator stress, failure limits, and axial strain at failure. The elastic modulus used in the mohr-coulomb analysis corresponds to the elastic modulus at 1% axial strain (Baziar et al., 2006). The results of the triaxial testing of the Manikin Dam asphalt concrete core are presented in Figure 2 and Table 1**.**

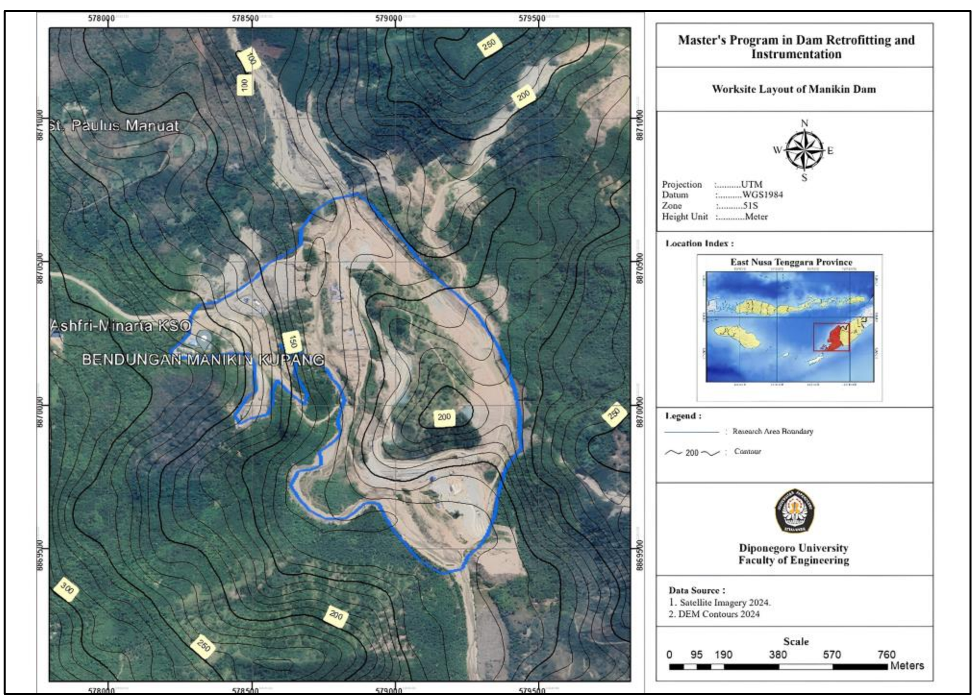

Figure 1. Location Map of Manikin Dam, Kupang Regency, East Nusa Tenggara.

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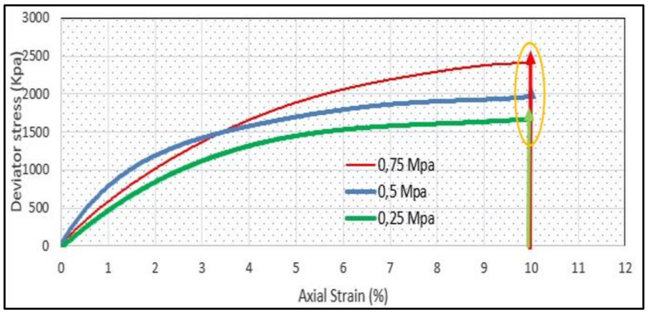

Figure 2. Triaxial Test Graph of Manikin Dam Asphalt Concrete.

The hardening soil material model enables a relatively accurate simulation of the behavior of frictional materials such as gravel and sand. In Hardening soil modeling, three key parameters are required: E50, Eeod, and Eur. The tangent modulus is obtained from the triaxial test graph, representing the modulus value when the stress reaches 50%, serving as an average value for various soil types. The relationships Eur ≈ 3E50 and Eeod ≈ E50 are commonly used (Tazakka, 2024). The hardening soil parameter values for the asphalt concrete core at different confining stresses are presented in Table 2, while the input parameters for Manikin Dam in Plaxis 2D V22 are provided in Table 3.

Table 1. Triaxial Test Results of Manikin Dam Asphalt Concrete

Bitumen content (%)	*Confining Stress* (Mpa)	*Deviator Stress at Failure* (Mpa)	*Axial Strain Of Failure* (%)	*E 1% axial Strain* (Mpa)	*v* (%)
7.00	0.25	1.70	10	46.50	0.45
	0.50	2.00	10	78.60	0.42
	0.75	2.40	10	58.90	0.37

Table 2. Hardening soil Parameter Values for Manikin Dam Asphalt Concrete

Deviator Stress at 1% (Kpa)	*Deviator Stress at 1% For E50* (Kpa)	*Strain For E50* (%)	E50 (Mpa)	Eeod (Mpa)	Eur (Mpa)
465	232.50	0.47	49.66	49.66	148.98
786	393.00	0.40	97.57	97.57	292.72
589	294.50	0.43	67.83	67.83	203.48

Table 3. Embankment Zone Parameter Values of Manikin Dam

Number	Zone Parameters		Zone 1 (Asphalt Core)		Zone 2 (Fine Filter)	Zone 3 (Coarse Filter)	Zone 4 (Fragmental Limestone)	Zone 5 (Coralline Limestone)	Plinth	Foundation Elevation +103 masl	Foundation Elevation +98 masl	Foundation Elevation +93 masl
1	Model		MC	HS	MC	MC	MC	MC	LE	MC	MC	MC
2	E	(Mpa)	58.90	-	90.00	100.00	27.65	27.65	17915.57	253.28	794.91	1470.90
3	E50	(Mpa)	-	67.83	-	-	-	-	-	-	-	-
4	Eeod	(Mpa)	-	67.83	-	-	-	-	-	-	-	-
5	Eur	(Mpa)	-	203.48	-	-	-	-	-	-	-	-
6	v		0.37	0.35	0.35	0.35	0.40	0.40	0.15	0.23	0.35	0.40
7	C	(kN/m²)	423.65	423.65	-	-	1.00	1.00	-	4.61	61.10	21.18
8	γ_{sat}	(kN/m³)	23.42	23.42	21.18	21.61	19.84	19.84	-	21.36	20.81	20.60
9	γ_{unsat}	(kN/m³)	23.42	23.42	17.95	18.85	16.31	16.31	19.13	16.28	16.28	15.79
10	e_{nit}		2.36	2.36	0.79	0.79	0.52	0.52	0.50	0.59	0.59	0.71
11	φ	(º)	24.58	24.58	36.00	38.67	40.00	40.39	75.00	34.34	34.21	30.48
12	ψ	(º)	0.00	0.00	6.00	8.67	10.00	10.39	45.00	4.34	4.21	0.48
13	K	(m/day)	8.64E-08	8.64E-08	5.14E+00	9.33E+00	4.99E+01	7.50E+01	8.64E-06	3.72E-03	6.31E-03	7.86E-03

Note: Mc (Mohr-Coulomb) and Hs (Hardening Soil).

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2.2. Research Methodology

The geometry of the Manikin Dam body is analyzed using a cross-section at STA 0+225, as this section represents the largest dam body dimensions located at the deepest part of the riverbed. The simulated design geometry includes foundation elevations at 103 masl and 98 masl, resulting in modeled dam heights of 50 meters and 55 meters in Plaxis 2D software. Each embankment layer is simulated with a height increment of 5 meters, with a construction duration of 18 days per layer. Plaxis is a finite element software used for geotechnical applications, providing various soil material models to simulate soil behavior (Bokko, 2019).

In Plaxis, a structure is discretized into smaller elements through a meshing process (Sari, UC; Sholeh, 2022). The asphalt concrete core material in the Plaxis simulation is modeled using Mohr-coulomb and hardening soil models. The mohr-coulomb model represents elastic perfectly plastic behavior, utilizing five material parameters: elastic parameters (elastic modulus (E) and Poisson's ratio (v)) and plastic parameters (internal friction angle (φ), cohesion (c), and dilation angle (ψ)) (Riza, 2014). The hardening soil model, on the other hand, more accurately represents hyperbolic stress-strain behavior. This model is based on plasticity theory rather than elasticity theory, accounting for soil dilatancy and incorporating a yield limit.

The hardening soil model considers the stress-dependent stiffness of soil under oedometric and deviatoric loading, as well as during primary loading, unloading, and reloading (Tschernutter & Kainrath, 2017). Vertical Deformation Analysis using Plaxis 2D software was conducted based on the staged embankment construction of the asphalt concrete core dam. As the height of the asphalt concrete core embankment increases, it influences the dam's safety factor. As the dam height increases, the safety factor decreases (Shiravi & Razmkhah, 2021).

The minimum safety factor for slope stability analysis upon completion of construction is 1.3 (SNI 8062, 2015). The static analysis of embankment dams follows general principles, where the initial geometry is simplified by merging multiple zones with similar material parameters into a single zone. The analysis applies linear constitutive laws and is conducted using total stress analysis (Petkovski et al., 2020). In this deformation analysis, Zone 6 (Riprap) was simplified into Rockfill Zone (Zones 4 & 5), as illustrated in Figure 3.

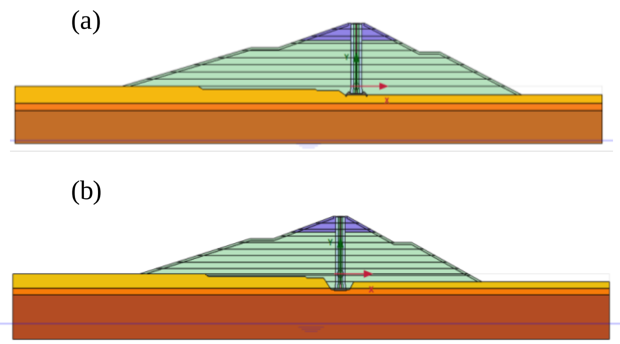

Figure 3. Manikin Dam Geometry. (a) Foundation elevation at 98 masl, (b) Foundation elevation at 103 masl.

The vertical deformation at the crest of a rockfill dam typically ranges between 0.2% to 1% of the total dam height (ICOLD, 1993). In Indonesia, the permissible settlement for dams is 2% (DPU Ditjen Pengairan Direktorat Bina Teknik, 1999). The maximum vertical deformation limit based on ICOLD standards is plotted on a vertical deformation trend graph for various dams. This plot is used to identify potential "abnormal" deformation behavior of the core during embankment construction. The total core settlement or central embankment zone settlement during the construction period versus dam height is presented in Figure 4.

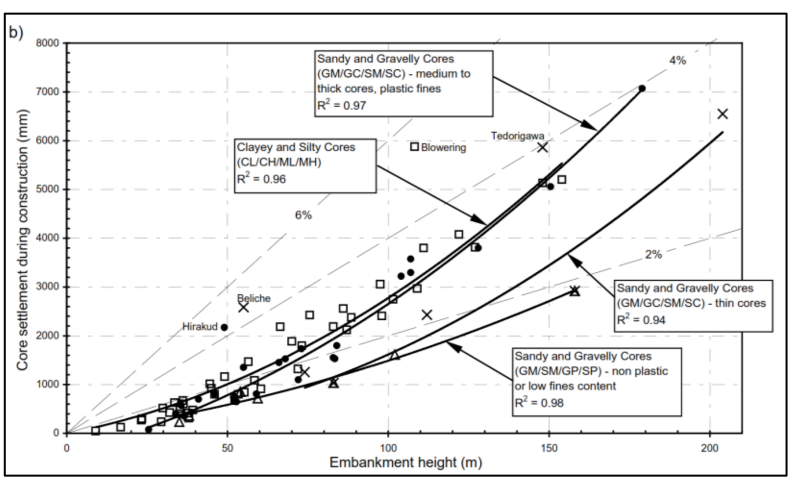

Figure 4. Graph of Vertical Settlement Relationship in the Dam Core with Height. (Hunter & Fell, 2003)

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3. Results and Discussion

3.1. Stability and Vertical Deformation at 25% Embankment Height Increase

The stability analysis of the dam begins with modeling the embankment height increase. Parent analysis is conducted to determine the initial static stress for each embankment layer, which originates from the overburdened soil pressure. The asphalt concrete core zone is simulated using two material models: Mohr-coulomb and hardening soil. The filter and rockfill zones utilize the mohr-coulomb model, while the plinth/concrete cap is modeled as a linear elastic material. The results of the Plaxis modeling for foundation elevations of 98 masl and 103 masl, based on the 1/4 (25%) embankment height increment simulation, are as follows. For the 103 masl foundation elevation, the mohr-coulomb core model yields a safety factor of 1.789 and a vertical deformation of 4.83 cm, whereas The hardening soil core model results in a safety factor of 1.789 and a vertical deformation of 4.75 cm. For the 98 masl foundation elevation, the mohr-coulomb core model produces a safety factor of 1.854 and a vertical deformation of 2.45 cm, while the hardening soil core model gives a safety factor of 1.855 and a vertical deformation of 2.47 cm. A negative vertical deformation value (Uy) indicates downward displacement. The results of the Plaxis simulation for the 1/4 (25%) embankment height increment are presented in Figure 5.

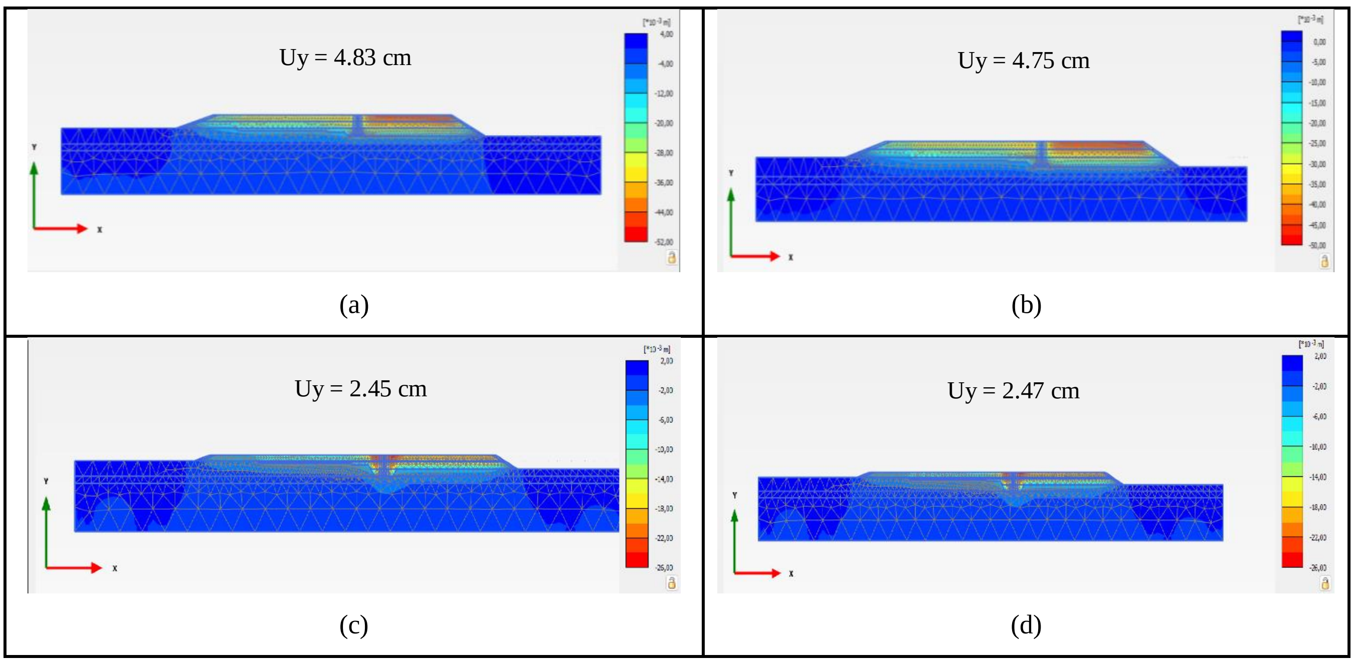

Figure 5. Vertical Deformation at 25% Embankment Height Increase. (a) Mc Foundation Elevation 103 masl, (b) Hs Foundation Elevation 103 masl, (c) Mc Foundation Elevation 98 masl, (d) Hs Foundation Elevation 98 masl.

3.2. Stability and Vertical Deformation at 50% Embankment Height Increase

The results of the Plaxis modeling for foundation elevations of 98 masl and 103 masl, based on the 2/4 (50%) embankment height increment simulation, are as follows. For the 103 masl foundation elevation, the mohr-coulomb core model yields a safety factor of 1.732 and a vertical deformation of 11.91 cm, whereas The hardening soil core model results in a safety factor of 1.736 and a vertical deformation of 11.76 cm. For the 98 masl foundation elevation, the mohr-coulomb core model produces a safety factor of 1.764 and a vertical deformation of 7.19 cm, while the hardening soil core model gives a safety factor of 1.770 and a vertical deformation of 7.19 cm. A negative vertical deformation value (Uy) indicates downward displacement. The results of the Plaxis simulation for the 2/4 (50%) embankment height increment are presented in Figure 6.

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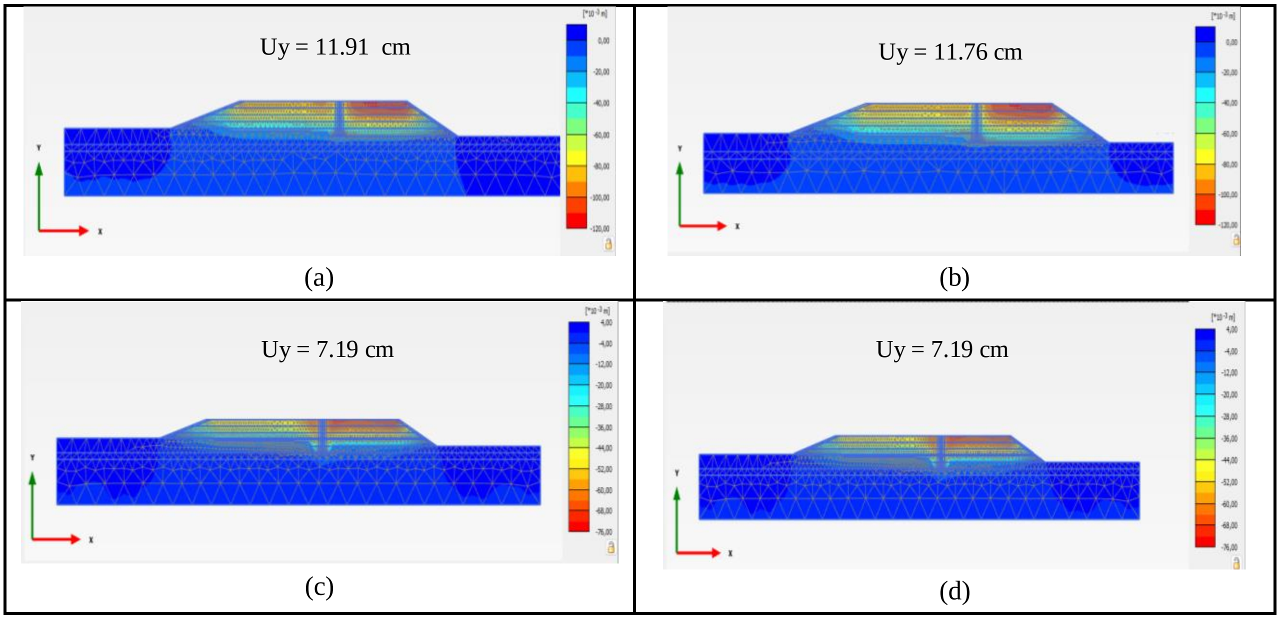

Figure 6. Vertical Deformation at 50% Embankment Height Increase. (a) Mc Foundation Elevation 103 masl, (b) Hs Foundation Elevation 103 masl, (c) Mc Foundation Elevation 98 masl, (d) Hs Foundation Elevation 98 masl.

3.3. Stability and Vertical Deformation at 75% Embankment Height Increase

The results of the Plaxis modeling for foundation elevations of 98 masl and 103 masl, based on the 3/4 (75%) embankment height increment simulation, are as follows. For the 103 masl foundation elevation, the mohr-coulomb core model yields a safety factor of 1.725 and a vertical deformation of 25.99 cm, whereas The hardening soil core model results in a safety factor of 1.723 and a vertical deformation of 25.79 cm. For the 98 masl foundation elevation, the mohr-coulomb core model produces a safety factor of 1.724 and a vertical deformation of 20.35 cm, while the hardening soil core model gives a safety factor of 1.723 and a vertical deformation of 20.37 cm. A negative vertical deformation value (Uy) indicates downward displacement. The results of the Plaxis simulation for the 3/4 (75%) embankment height increment are presented in Figure 7.

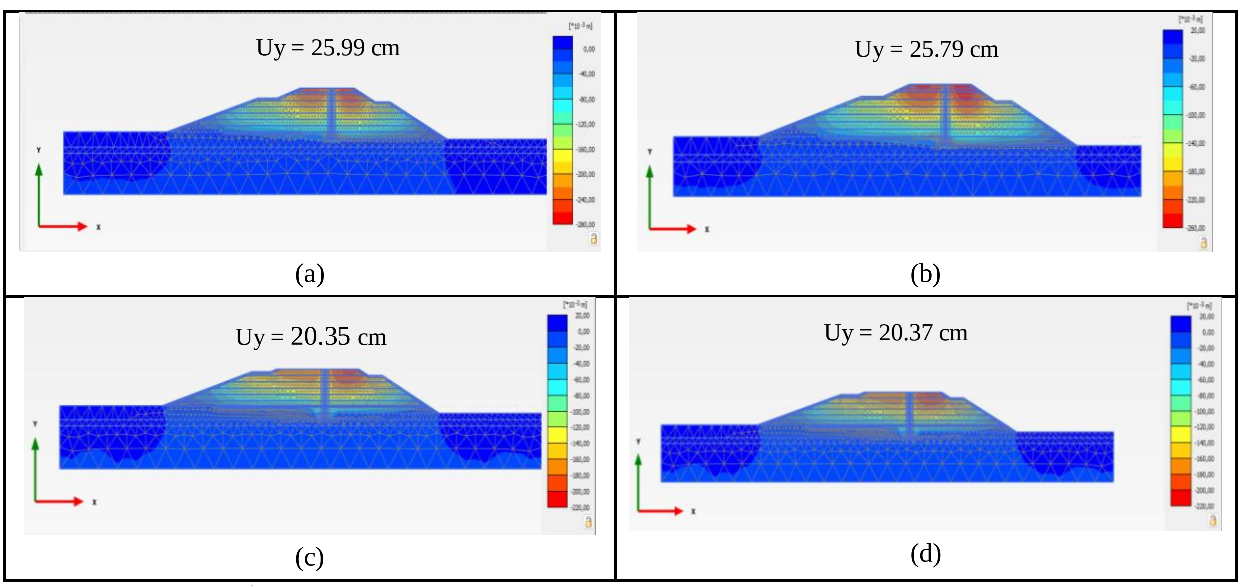

Figure 7. Vertical Deformation at 75% Embankment Height Increase. (a) Mc Foundation Elevation 103 masl, (b) Hs Foundation Elevation 103 masl, (c) Mc Foundation Elevation 98 masl, (d) Hs Foundation Elevation 98 masl.

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3.4. Stability and Vertical Deformation at 100% Embankment Height Increase.

The results of the Plaxis modeling for foundation elevations of 98 masl and 103 masl, based on the 100% embankment height increment simulation, are as follows. For the 103 masl foundation elevation, the mohr-coulomb core model yields a safety factor of 1.723 and a vertical deformation of 35.12 cm, whereas The hardening soil core model results in a safety factor of 1.720 and a vertical deformation of 35.74 cm. For the 98 masl foundation elevation**,** the mohr-coulomb core model produces a safety factor of 1.716 and a vertical deformation of 35.81 cm, while the hardening soil core model gives a safety factor of 1.724 and a vertical deformation of 36.69 cm**.** A negative vertical deformation value (Uy) indicates downward displacement. The results of the Plaxis simulation for the 100% embankment height increment are presented in Figure 8.

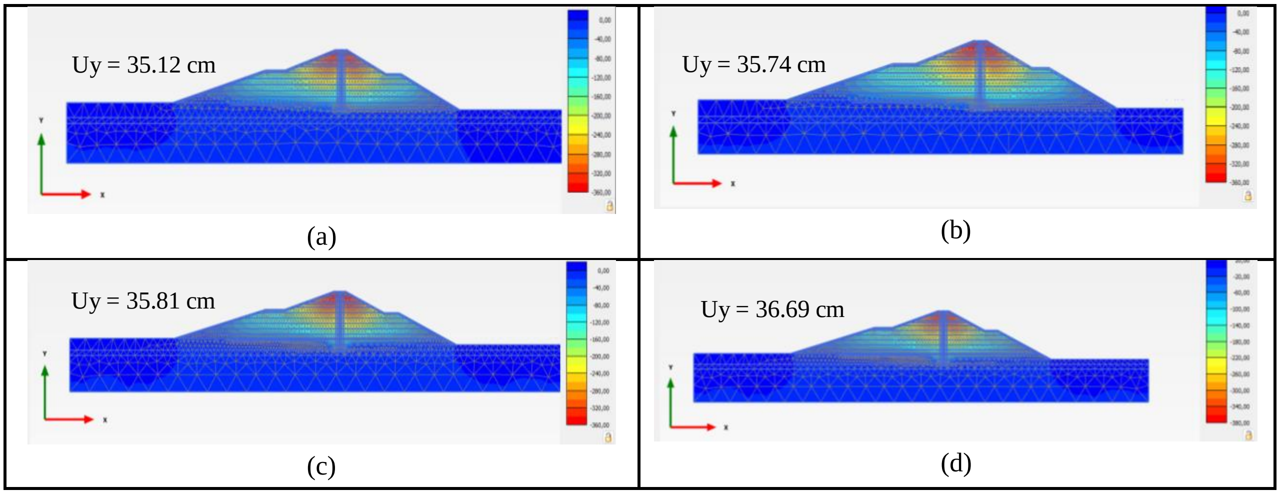

Figure 8. Vertical Deformation at 100% Embankment Height Increase. (a) Mc Foundation Elevation 103 masl, (b) Hs Foundation Elevation 103 masl, (c) Mc Foundation Elevation 98 masl, (d) Hs Foundation Elevation 98 masl.

3.5. Summary of Safety Factor Values and Vertical Deformation (Uy) Results

Based on the Plaxis modeling of the Manikin Dam design geometry at foundation elevations of 103 masl and 98 masl, a summary of the safety factor values for each embankment height increment and the vertical deformation (Uy) values is presented in Table 4 and Table 5. The summary graphs are shown in Figures 9 and 10.

Table 4. Summary of Safety Factor and Vertical Deformation Results for Each Embankment Height Increment at 103 masl Foundation Elevation

Number	Elevation	Safety Factor		Uy (cm)		Failure Criteria for Uy (cm)		Description
		Mc	Hs	Mc	Hs	ICOLD	PU	
1	109.00	1.955	1.955	0.86	0.84	50	100	Accepted
2	114.00	1.842	1.844	2.45	2.40	50	100	Accepted
3	119.00	1.789	1.789	4.83	4.75	50	100	Accepted
4	124.00	1.760	1.760	7.98	7.87	50	100	Accepted
5	129.00	1.732	1.736	11.91	11.76	50	100	Accepted
6	134.00	1.724	1.723	16.27	16.06	50	100	Accepted
7	139.00	1.726	1.726	21.01	20.77	50	100	Accepted
8	144.00	1.725	1.723	25.99	25.79	50	100	Accepted
9	149.00	1.730	1.728	31.02	31.09	50	100	Accepted
10	153.00	1.723	1.720	35.12	35.74	50	100	Accepted

Note: Mc (Mohr-coulomb) and Hs (Hardening soil).

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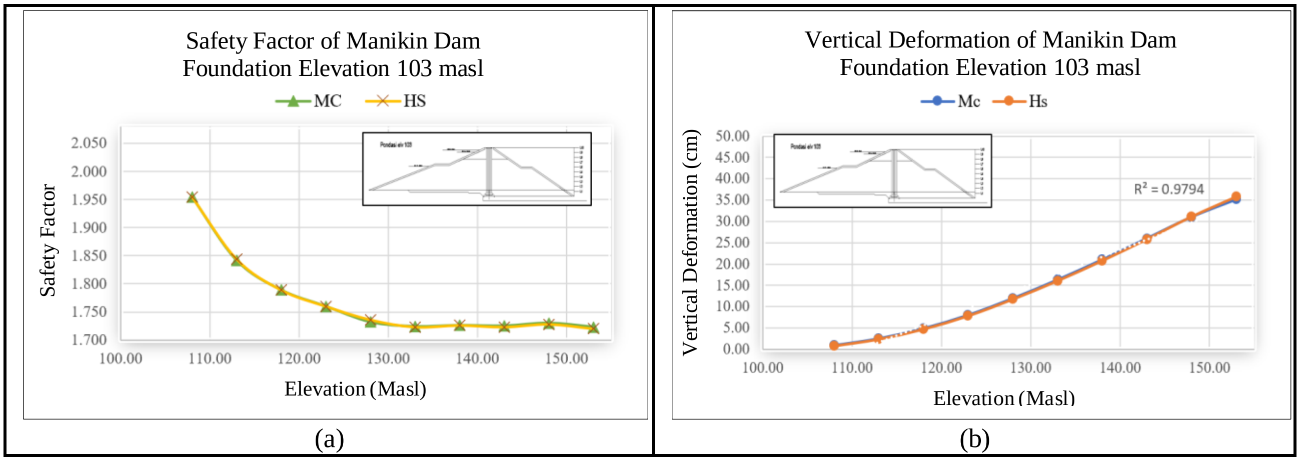

Figure 9. Graph of Manikin Dam at 103 masl Foundation Elevation. (a) Safety Factor for Each Embankment Height Increment, (b) Vertical Deformation for Each Embankment Height Increment.

Table 5. Summary of Safety Factor and Vertical Deformation Results for Each Embankment Height Increment at 98 masl Foundation Elevation

Number	Elevation	Safety Factor		Uy (cm)		Failure Criteria for Uy (cm)		Description
		Mc	**Hs**	**Mc**	**Hs**	**ICOLD**	**PU**	
1	103.00	1.681	1.673	0.44	0.44	55	110	Accepted
2	108.00	2.007	2.010	1.25	1.25	55	110	Accepted
3	113.00	1.854	1.855	2.45	2.47	55	110	Accepted
4	118.00	1.794	1.799	4.31	4.32	55	110	Accepted
5	123.00	1.764	1.770	7.19	7.19	55	110	Accepted
6	128.00	1.745	1.737	10.95	10.95	55	110	Accepted
7	133.00	1.728	1.728	15.56	15.55	55	110	Accepted
8	138.00	1.724	1.723	20.35	20.37	55	110	Accepted
9	143.00	1.723	1.722	25.64	25.73	55	110	Accepted
10	148.00	1.727	1.730	30.77	31.03	55	110	Accepted
11	153.00	1.716	1.724	35.81	36.69	55	110	Accepted

Note: Mc (Mohr-coulomb) and Hs (Hardening soil).

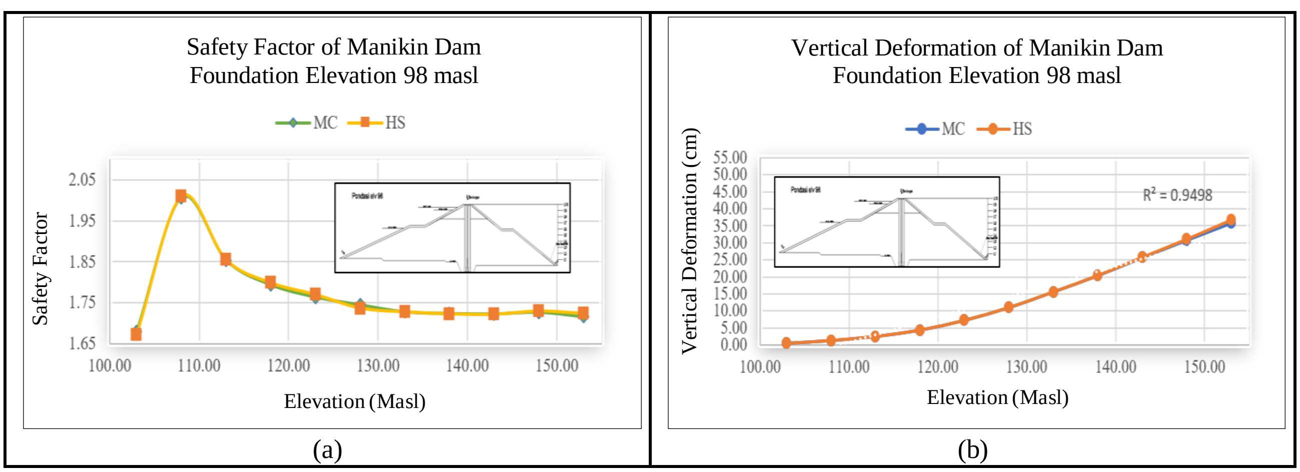

Figure 10. Graph of Manikin Dam at 98 masl Foundation Elevation. (a) Safety Factor for Each Embankment Height Increment, (b) Vertical Deformation for Each Embankment Height Increment.

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The summary tables and graphs for the Manikin Dam geometry at foundation elevations of 103 masl and 98 masl indicate that modeling asphalt as a hardening soil material model results in more conservative safety factor values compared to the mohr-coulomb model across all embankment height increments. Studies on asphalt concrete core dams indicate that the safety factor decreases as the embankment height increases (Shiravi & Razmkhah, 2021). The safety factor behavior at the first embankment layer differs between the 103 masl and 98 masl foundation elevations, likely due to the steep excavation geometry of the riverbed. Vertical deformation patterns also differ at each embankment height increment for both foundation elevations. For the Manikin Dam geometry at 103 masl, the mohr-coulomb model produces higher average vertical deformation at each embankment height increment compared to the hardening soil model. This observation aligns with research comparing embankment dam deformation using mohr-coulomb and hardening soil models, which found that mohr-coulomb predicts vertical deformation values 50-58% higher than Hardening soil. This suggests that the mohr-coulomb model tends to overestimate vertical deformation (Bhutto et al., 2019). For the Manikin Dam geometry at 98 masl, The hardening soil model produces higher average vertical deformation at each embankment height increment compared to mohr-coulomb, indicating that vertical deformation behavior is influenced by the embankment design geometry. The vertical deformation values were plotted on a graph of total core settlement versus dam height during construction. The Manikin Dam, with an asphalt concrete core, is classified as a thin-core dam, as its core thickness is less than 0.25H:1V. The vertical deformation trend of the Manikin Dam asphalt core falls below that of several other dams, including those with sand and gravel cores classified as thin-core dams. The vertical deformation plot of the Manikin Dam is presented in Figure 11.

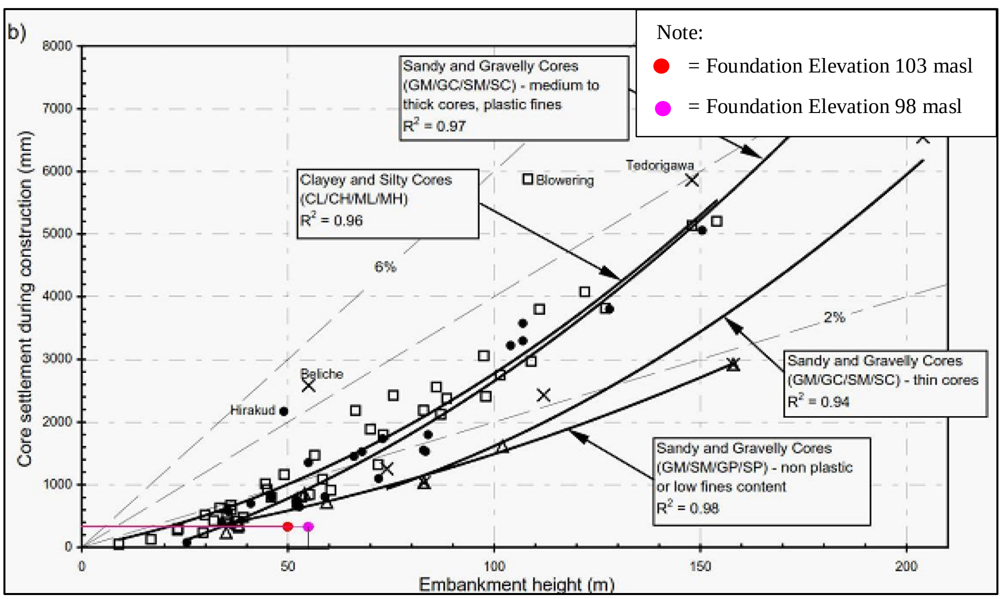

Figure 11. Total Core Settlement of the Embankment Dam During the Construction Period vs. Dam Height (Hunter & Fell, 2003)

4. Conclusion

Based on the Plaxis 2D modeling of the two geometric designs of the Manikin Dam, the following conclusions were obtained. Vertical deformation (Uy) at each embankment height increment exhibits a consistent trend for both dam geometries, where vertical deformation increases as the embankment height increases. The safety factor values, when modeling asphalt as a hardening soil material, are more conservative than those obtained using the mohr-coulomb model, on average, for each embankment height increment.

The vertical deformation behavior differs between the mohr-coulomb and hardening soil models, depending on the dam's design geometry. The plotted vertical deformation values on the core settlement vs. dam height graph indicate that the asphalt core deformation is lower than that of other dams with sand and gravel cores classified as thin-core dams. The vertical deformation resulting from changes in the Manikin Dam core height remains within the permissible limits set by ICOLD and PU.

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