Finite Element Analysis of Slope Stability Reinforced with Corrugated Concrete Sheet Pile

Dewa Ngakan Putu Ananda Parwita[1], I Gede Ngurah Arya Yudistira[1*]
Civil Engineering, Udayana University, Bali[1]
[*]E-mail address: arya.yudistira@unud.ac.id

ABSTRACT

Slope instability is a major challenge in coastal and soft ground areas, posing risks to infrastructure and safety. This study presents an applied case study of slope reinforcement at Tanjung Batu, East Kalimantan, using Corrugated Concrete Sheet Pile (CCSP) evaluated through finite element analysis in PLAXIS 2D. The numerical results indicate that CCSP installation significantly increases the factor of safety from 1.493 to 1.922 of the slope and that the selected pile section (CCSP W-400) performs structurally within safe limits under anticipated loading. These findings demonstrate the practical effectiveness of prefabricated concrete sheet piles for improving slope stability in soft ground conditions. While the study is limited to numerical simulations, it provides useful insights for engineering practice and highlights the need for field validation and long-term performance monitoring.

Keywords: Corrugated Concrete Sheet Pile (CCSP); Finite element method; Numerical analysis; PLAXIS 2D; Slope stability.

1. INTRODUCTION

Slope instability and failure are among the most pressing geotechnical challenges faced in civil infrastructure, especially in regions with varied topography, high rainfall intensity, or increasing land development pressures. Landslides, as a common manifestation of slope failure, pose significant risks to human life, infrastructure, and the environment.

On this study on this case, it is located in Kutai Kertanegara, East Kalimantan. Figure 1 shows the area surrounding of PLTGU Tanjung Batu in Kutai Kartanegara, East Kalimantan, the site is located within the Mahakam River basin and exhibits typical characteristics of East Kalimantan's alluvial and sedimentary plains. Based on environmental impact assessments, geological surveys, and laboratory studies, the dominant soil types in this region are classified as Ultisols (Podsolik Merah Kuning), with patches of peat and alluvial soils in certain low-lying or floodplain areas [1], [2].

The implementation of engineered slope reinforcement systems is very much needed. One way to achieve slope stability is to install such a system that helps or reinforce the slope. Traditional method that can be installed is retaining wall, terracing and vegetation. Among these, the use of retaining systems such as sheet piles has proven effective in enhancing slope stability. The effectiveness of sheet pile reinforcement has been demonstrated in numerous studies employing both field measurements and numerical simulations, In some cases where a retaining wall alone was insufficient, the implementation of CCSP reinforcement raised the slope's safety factor from unsafe values (SF = 0.52) to stable levels (SF = 1.58)[3].

Figure 1. Site Location of PLTGU Tanjung Batu

Recent advancements have introduced Corrugated Concrete Sheet Piles (CCSP), combining structural rigidity with constructability and cost-efficiency. Numerical modeling utilizing finite element software, such as Plaxis 2D, has further enabled precise simulation and analysis of reinforced slope behavior under various loading and environmental conditions, leading to optimal design and performance assessment[4].

The utilization of Corrugated Concrete Sheet Piles (CCSP) in slope stabilization offers multiple advantages that make this approach highly effective. One of the critical innovations in CCSP technology is the introduction of corrugation design. Unlike traditional flat sheet piles, the corrugated geometry significantly improves the flexural stiffness of the pile. Flexural stiffness is crucial for resisting lateral pressures from soil and water, especially in slope retention and riverbank stabilization projects[5]. The corrugated design optimizes the moment of inertia which, in turn, increases the resistance to bending under high loads. This enhanced resistance is vital for protecting against slope failures and minimizing soil displacement in areas prone to landslides.

Based on availability of CCSP on the site, this study aims to evaluate the effectiveness of corrugated concrete sheet piles in improving slope stability through finite element analysis. This study aims to analyze the safety factor of the slope before and after CCSP installation by using numerical analysis (FEM) Plaxis 2D.

2. THEORY AND METHODS

2.1. Theory

Slope stability analysis is an essential aspect of geotechnical engineering, particularly in regions where natural or man-made slopes are prevalent and pose risks to infrastructure and human safety. Several analytical and numerical methods exist for evaluating slope stability. Traditional limit equilibrium methods, such as the Bishop, Janbu, and Morgenstern-Price methods, assume potential slip surfaces and calculate factors of safety (FoS) based on force and moment equilibrium states. More advanced numerical methods, such as finite element and finite difference analyses, enable the modeling of complex slope behavior, including non-linear material properties, heterogeneity, staged construction, and reinforcement effects.

Limit equilibrium methods

In the study of slope stability, the Limit Equilibrium Method (LEM) has long been recognized as one of the most widely used analytical procedures, both in academic research and engineering practice. The method is particularly valued for its ability to provide approximations of the factor of safety (FoS) for slopes in a range of geotechnical contexts[6]. The LEM assumes the potential failure surface within the soil mass and considers the equilibrium of forces or moments acting on the soil above this surface. The soil shear strength along the assumed or computed slip surface is typically represented via the Mohr-Coulomb failure criterion, which relates shear strength to the normal effective stress which expressed on Equation (1).

$$\tau = c + \sigma' \tan \phi \tag{1}$$

where τ is the shear strength, c is the cohesion, σ' is the effective normal stress, and ϕ is the internal angle of friction[7].

Slice-based methods, such as the Bishop, Fellenius, and Janbu approaches, are commonly applied within the LEM framework to analyze more complex or heterogeneous slopes or when stabilization methods alter the stress distribution. The factor of safety is expressed on Equation (2).

$$SF = \frac{\tau_f}{\tau_d} \tag{2}$$

Where τ_f is the available shear strength and τ_d the mobilized shear stress along the slip surface. When the factor of safety (FoS) is less than 1.0, the slope is judged unstable; a value greater than 1.0 is required for stability.

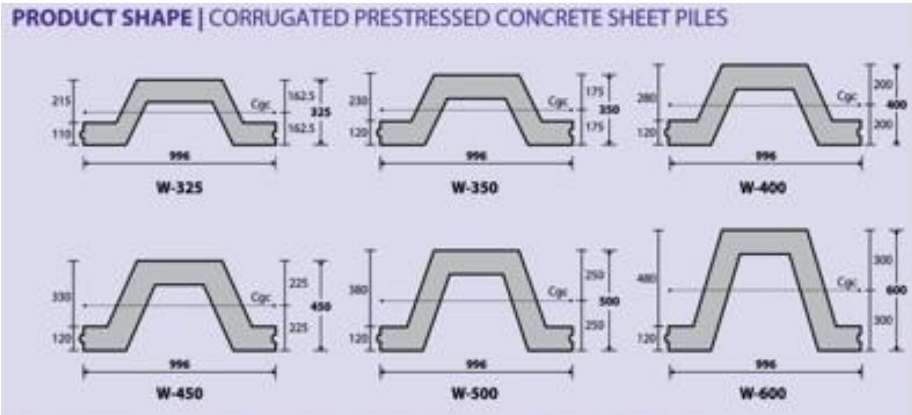
Finite element methods

The application of the finite element method (FEM) in slope stability analysis has evolved into a robust standard approach in geotechnical engineering, offering significant advantages over traditional methods such as limit equilibrium. Unlike limit equilibrium methods, which require a priori assumptions about the geometry of potential failure surfaces, the FEM determines failure modes and the corresponding factor of safety (FOS) through a comprehensive assessment of the stress-strain relationships and constitutive behavior of the slope materials[8], [9], [10].

A new advancement in FEM based slope stability is the implementation of the Shear Strength Reduction (SSR) technique, wherein the shear strength parameters of the soil are systematically scaled until global failure is indicated by excessive displacements or non-convergence in the numerical solution[11]. This approach naturally captures complex failure mechanisms, including multiple or non-circular slip surfaces, which are particularly relevant in heterogeneous or reinforced slopes.

Corrugated Concrete Sheet Pile (CCSP)

Corrugated Concrete Sheet Pile (CCSP) is a specialized type of precast concrete sheet pile engineered with a corrugated profile that enhances its mechanical interlock and structural efficiency. The design of these piles typically integrates a tongue-and-groove or grouted joint system which, when driven into the ground, allows for the construction of continuous, water-resistant retaining walls. The corrugated geometry not only improves bending stiffness and load distribution but also increases interface friction with surrounding soil, contributing to overall stability, particularly in challenging geotechnical scenarios such as slopes or deep excavations. Figure 3 shows typical shapes and technical data for CCSP.



SPECIFICATION | CORRUGATED PRESTRESSED CONCRETE SHEET PILES

Concrete Compressive Strength fc' = 62,5 MPa *Unit Conversion 1 Ton = 9,806 kN*

Type	Thickness (mm)	Width (mm)	Cross Section (cm²)	Section Inertia (cm⁴)	Unit Weight (kg/m)	Class	Moment (kN.m)		Length* (m)
							Crack	Break	
W-325	110	996	1.315	134.264	329	A	112	224	8 - 15
						B	130	261	8 - 16
W-350	120	996	1.468	169.432	368	A	153	306	9 - 17
						B	167	333	10 - 17
W-400	120	996	1.598	248.691	400	A	197	394	10 - 17
						B	229	459	11 - 19
W-450	120	996	1.835	353.363	459	A	264	528	11 - 19
						B	301	602	12 - 21
W-500	120	996	1.818	462.373	455	A	345	690	12 - 22
						B	396	792	13 - 24
W-600	120	996	2.078	765.907	520	A	496	992	14 - 25
						B	584	1.169	15 - 27

*Note : *) Length of Concrete Corrugated Sheet Piles may exceed usual standard whenever lifted in certain position*

Figure 2. Typical datasheets of Corrugated Concrete Sheet Piles

2.2. Methods

Study Area and data collection

The study area at Tanjung Batu, East Kalimantan, was selected based on prior geotechnical site investigations and slope instability concerns. Relevant geological and soil parameters including soil unit weight, cohesion, and internal friction angle were collected from borehole logs and laboratory tests to define accurate input parameters for numerical modeling[12]. These input soil parameters are summarized in Table 1.

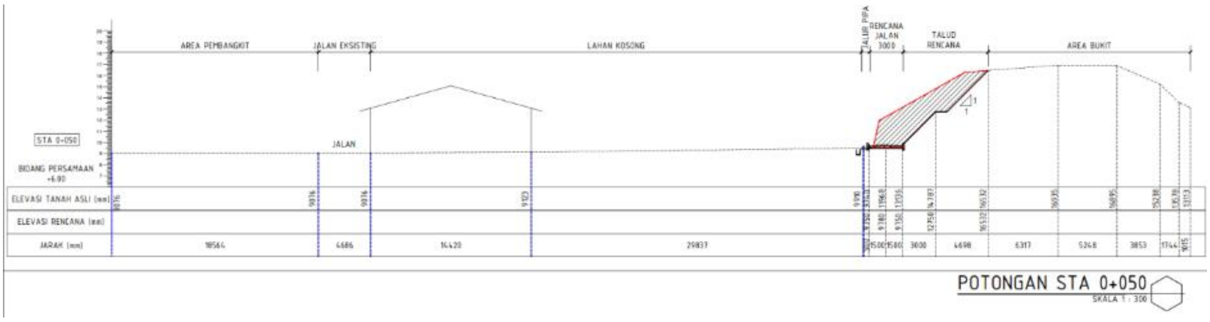


Figure 3. Cut section of the slope used in Plaxis 2D modeling.

For this case, the Hardening Soil (HS) model was adopted due to its capacity to represent the non-linear, stress-dependent, and anisotropic behaviors typical of stiff clays under various loading conditions[13]. Comprehensive studies, such as [14], have demonstrated that the HS model yields better agreement with laboratory and field behavior for both soft and stiff clays when compared to more simplistic approaches.

Figure 4. Layout View Earth PLTGU Tanjung Batu

Table 1. Soil Input Parameter

INPUT SOIL						
Refrence Boring Hole				**B1 AND LAB**		
Identification		**1. Stiff Clay (LAB)**	**2. Stiff Clay (LAB)**	**3. Very Stiff Clay**	**4. Hard Clay**	**5. Stiff Clay (LAB)**
Mateiral Model		Hardening Soil (HS)	Hardening Soil (HS)	Hardening Soil (HS)	Hardening Soil (HS)	Hardening Soil (HS)
Drainage Type		Drained	Drained	Drained	Drained	Drained
Colour						
Layer Depth		0 - 4	4 - 8	8 - 12	12 - 30	0 - 4
			General Properties			
g_{unsat}	kN/m^3	13.70	19.30	18.10	19.56	19.50
g_{sat}	kN/m^3	15.70	21.30	20.10	21.56	21.50
			Stiffness			
E'_{rm}	kN/m^2	-	-	-	-	-
v'	-	0.30	0.30	0.30	0.30	0.30
E_{50}^{ref}	kN/m^2	20300.00	20300.00	20300.00	31500.00	20300.00
E_{oed}^{ref}	kN/m^2	22560.00	22556.00	22556.00	35000.00	22560.00
E_{ur}^{ref}	kN/m^2	60900.00	60900.00	60900.00	94500.00	60900.00
Power (m)	-	1.00	1.00	1.00	1.00	1.00
l (Lambda)	-	-		-	-	-
k (Kappa)	-	-		-	-	-
Cc	-	-		-	-	-
Cs	-	-		-	-	-
$e_{initial}$	-	0.70	0.690	0.690	0.477	0.700
			Strength			
C'_{ref}	kN/m^2	17.50	17.33	50.00	50.00	17.50
f(phi)	degree	31.00	20.06	25.00	25.00	31.00
y(psi)	degree	0.00	0.00	0.00	0.00	0.00
			Ground Water			
Type	-	Clay	Clay	Clay	Clay	Clay
Kx	m/day	From Data Set	6.05E-03	6.05E-03	8.02E-03	From Data Set
Ky	m/day	From Data Set	6.05E-03	6.05E-03	8.02E-03	From Data Set
			Interface			
Strength	-	Manual	Manual	Manual	Manual	Manual
R_{inter}	-	0.50	0.50	0.50	0.50	0.90

FEM Modelling

A two-dimensional slope stability model was developed using finite element software Plaxis 2D as shown on Figure 5. The model domain was geometrically designed to replicate the natural slope profile and boundary conditions observed in the field. The base and lateral boundaries were assigned fixed constraints to simulate an infinite soil continuum, preventing displacement at model edges[15]. The slope was analyzed in two conditions: (1) without reinforcement (baseline), and (2) with CC Sheet Pile reinforcement. Additionally, deflection and bending moment of the sheet pile were monitored to assess the pile's structural performance and its effectiveness in slope stabilization. Displacement contours and failure surfaces were extracted to identify slip mechanisms and deformation patterns.

The initial simulation was conducted on the unreinforced slope to establish the baseline safety factor (SF) and failure mechanism. The Corrugated Concrete Sheet Pile (CCSP) was added into the model as a structural reinforcement element embedded to a designed depth relevant to expected sliding surfaces[16]. Mechanical properties of the sheet pile, including stiffness and bending resistance, were assigned based on manufacturer specifications. Interface elements between soil and sheet pile were defined to realistically model adhesion and possible slip effects.

The selected sheet pile type for this study is the CCSP W-400, which has a maximum cracking moment capacity of 197 kNm and an ultimate bending (break) moment capacity of 394 kNm. The proposed design involves installing the sheet pile to a total length of 12 meters. The used parameter for this structured is shown on Table 2. This selection aims to ensure that the sheet pile can accommodate the calculated maximum bending moment while providing adequate structural performance and serviceability under the expected loading conditions.

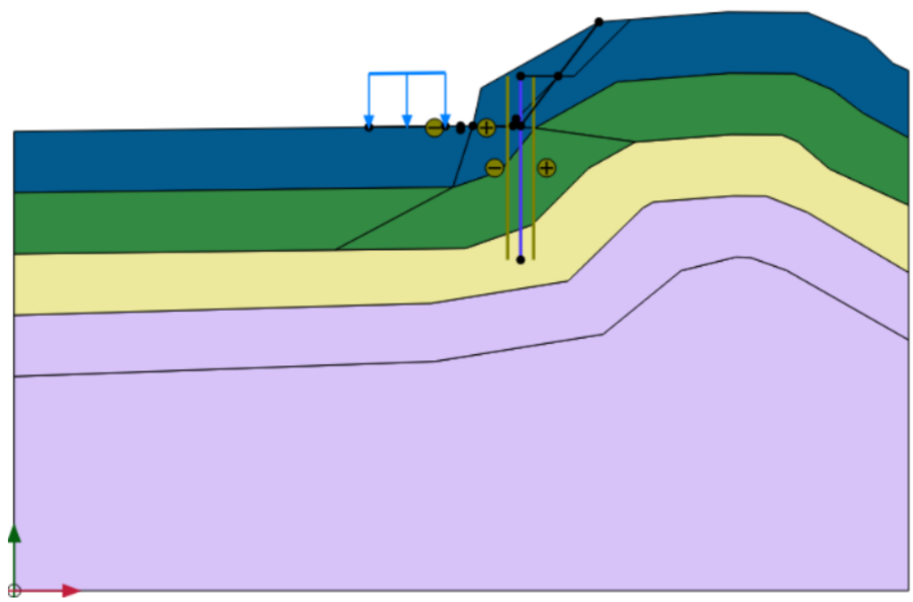


Figure 5. Model on Plaxis2D

Table 2. Corrugated Concrete Sheet Pile (CCSP) Input Parameter on Plaxis 2D

INPUT PARAMETER STRUCTURE		
Identification		**CCSP W-400(A)**
Set Type		Plate
Comment		-
Material type		Elastoplastic
Properties		
E	kN/m^2	37156762.51
g	kN/m^3	24
Predifined beam type		-
width	m	-
Lspacing	m	-
EA1	kN/m	5937650.65
EA2	kN/m	5937650.65
EI	kN.m^2/m	92405.52
w	kN/m/m	1.44
v(nu)	-	0.15
Mp	kNm	197
$N_{p,1} = N_{p,2}$	kN/m	0

The primary metric for this stability evaluation was the safety factor (SF). Improvement in SF after pile installation indicates enhanced slope stability. The deflection profiles of the Corrugated Concrete Sheet Pile provide critical data on structural deformation, with lower deflections suggesting better reinforcement performance. Comparative analysis of SF and deflections before and after reinforcement enabled quantitative assessment of CC Sheet Pile effectiveness.

3. RESULT AND DISCUSSION

Factor of safety without reinforcement

Based on the analysis conducted in Plaxis 2D shown in Figure 6, using the strength reduction method, the calculated factor of safety for the slope without reinforcement is **1.493**. According to the requirements of SNI 8460:2017, this value is considered inadequate, as it falls below the minimum recommended factor of safety of 1.50, indicating that the slope in its current condition is not sufficiently stable.

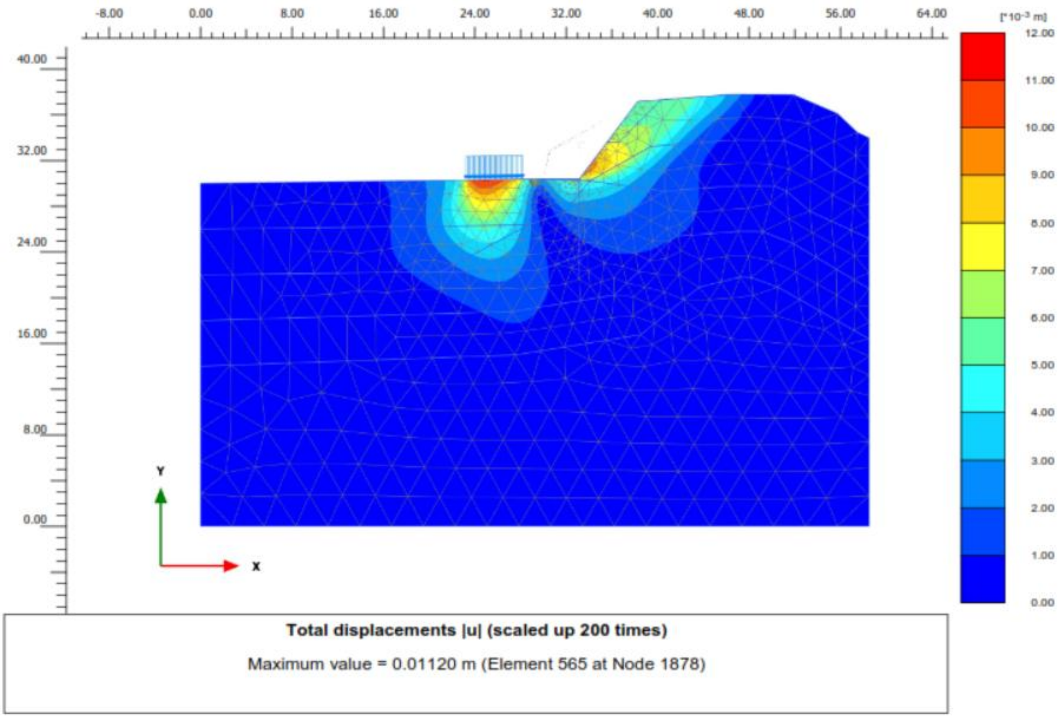


Figure 6. FEM Result without reinforcement.

Factor of safety with Sheet Pile reinforcement

Based on the analysis conducted using Plaxis 2D shown in Figure 7, with the strength reduction method, the calculated factor of safety for the slope reinforced with corrugated concrete sheet piles is **1.922**. According to the requirements of SNI 8460:2017, a minimum factor of safety of 1.50 is required to ensure stability under normal loading conditions.

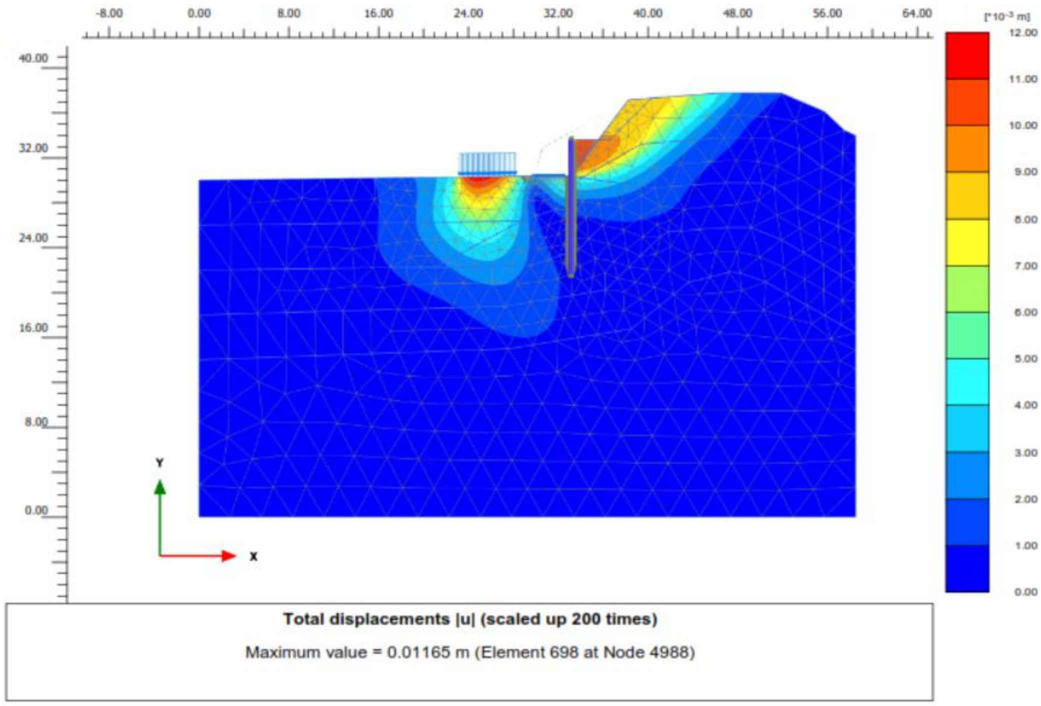


Figure 7. FEM Result with reinforcement.

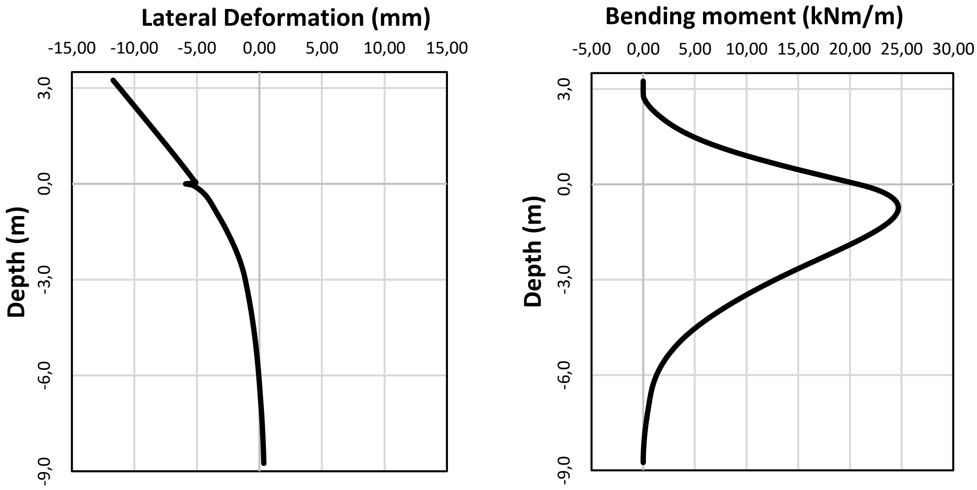


Figure 8. Deflection and Bending moment result from FEM analysis

Sheet pile deflection

In addition to the stability analysis, the lateral deflection of the sheet pile was evaluated to assess its structural performance. As shown in Figure 8, the numerical analysis conducted using Plaxis 2D yielded a maximum lateral deflection of approximately 11.705 mm and a maximum bending moment of 24.688 kNm/m. These results provide valuable insight into the deformation behavior and structural demand of the sheet pile under the modeled loading conditions. Referring to SNI 8460:2017, the maximum allowable deflection for sheet pile structures is 15 mm. Therefore, the observed deflection remains within acceptable limits, indicating that the proposed design satisfies serviceability criteria.

4. CONCLUSIONS

This study investigated the effectiveness of Corrugated Concrete Sheet Pile (CCSP) as a slope reinforcement system at Tanjung Batu, East Kalimantan, through finite element numerical analysis. The results show that installing CCSP significantly improves the slope's safety factor compared to unreinforced conditions, while the selected pile section (CCSP W-400) maintains safe bending performance under site conditions. These findings highlight CCSP's potential as a reliable and efficient solution for slope stabilization in coastal and soft soil areas where conventional methods may be less effective or more costly. In addition, the structural behavior of CCSP indicates good compatibility with the surrounding soil, ensuring overall system stability. The use of prefabricated concrete elements also suggests shorter construction times and reduced environmental disturbance compared to traditional approaches. However, as the study is limited to numerical simulations, field validation is needed to confirm long-term performance under factors such as cyclic loading, groundwater fluctuations, and material degradation. Future research should include field monitoring and large-scale testing to assess durability and constructability, supporting the integration of CCSP into design guidelines for safer and more resilient coastal infrastructure in Indonesia and similar environments.

REFERENCES

[1] R. Shanti and R. Nirmala, "Evaluation of post-mining land for rubber and oil palm plantations in Kutai Kartanegara, Indonesia," *J. Agric. Environ. Int. Dev.*, vol. 112, no. 1, pp. 25–42, 2018, doi: 10.12895/jaeid.20181.689.

[2] N. Sukarman, E. Suryani, and H. Husnain, "Land Suitability and Direction of Strategic Agricultural Commodities in East Kalimantan to Support the Development of the New Nation's Capital of Republic of Indonesia," *J. Sumberd. Lahan*, vol. 15, no. 1, p. 1, 2021, doi: 10.21082/jsdl.v15n1.2021.1-12.

[3] R. T. Lestari, A. H. Y, and M. G. Zuhdan, "ANALISIS PERBANDINGAN PERKUATAN DINDING PENAHAN TANAH DENGAN SHEET PILE," *Constr. Mater. J.*, vol. 7, no. 1, 2025.

[4] K. Jumadi, A. Dofir, A. Andreas, and N. Tinumbia, "ANALISIS STABILITAS TIMBUNAN MENGGUNAKAN CORRUGATED CONCRETE SHEET PILE (CCSP) DENGAN SOFTWARE PLAXIS 2D V22 (STUDI KASUS: RUAS JALAN SEKITAR GERBANG TOL SENTUL SELATAN) (Landfill Stability Analysis Using Corrugated Concrete Sheet Pile (CCSP) with Plaxis ," *J. Infrastruktur*, vol. 10, no. 1, pp. 25–34, 2024.

[5] A. Triarso and Y. Risdianto, "Corrugated Sheet Pile Analysis on Riverbank Retaining Wall Project in Factory Area of the Sukoraharjo Street," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1125, no. 1, p. 012018, 2021, doi: 10.1088/1757-899x/1125/1/012018.

[6] K. SaThierbach *et al.*, *Slope Stability Analysis by the Limit Equilibrium Method*, vol. 3, no. 1. 2015.

[7] H. Lin, W. Zhong, W. Xiong, and W. Tang, "Erratum: Slope stability analysis using limit equilibrium method in nonlinear criterion (The Scientific World Journal (2014) 2014 (206062))," *Sci. World J.*, vol. 2015, 2015, doi: 10.1155/2015/419636.

[8] Rocscience, "Application of the Finite Element Method to Slope Stability," in *Proceedings of the Institution of Civil Engineers*, 2001, pp. 2001–2004.

[9] I. N. Hamdhan, "Slope stability analysis with finite element method," *Karya Tulis Ilm. Itenas*, 2013.

[10] N. Anggraini, "Analisis Stabilitas Lereng Dengan Metode Elemen Hingga (Studi : Proyek New Priok Container Terminal)," *Bear. J. Penelit. dan Kaji. Tek. Sipil*, vol. 8, no. 1, p. 1, 2023, doi: 10.32502/jbearing.v8i1.6260.

[11] R. E. Hammah, J. H. Curran, T. Yacoub, and B. Corkum, "Analysis of rock slopes, using the finite element method," in *EUROCK 2004 & 53rd Geomechanics Colloquium. Schubert (ed.)*, 2004.

[12] J. Idrus, N. Hamzah, R. Ramli, M. M. Nujid, and S. F. Sadikon, "Enhancing Slope Stability with Different Slope Stabilization Measures: A Case Study using SLOPE/W Software," *J. Kejuruter.*, vol. 35, no. 6, pp. 1427–1434, 2023, doi: 10.17576/jkukm-2023-35(6)-15.

[13] T. A. Bower, A. D. Jefferson, and P. J. Cleall, "A reformulated hardening soil model," *Proc. Inst. Civ. Eng. Eng. Comput. Mech.*, vol. 173, no. 1, pp. 11–29, 2020, doi: 10.1680/jencm.18.00054.

[14] C. Surarak, S. Likitlersuang, D. Wanatowski, A. Balasubramaniam, E. Oh, and H. Guan, "Stiffness and strength parameters for hardening soil model of soft and stiff Bangkok clays," *Soils Found.*, vol. 52, no. 4, pp. 682–697, 2012, doi: 10.1016/j.sandf.2012.07.009.

[15] W. Chengzhong and N. Shuangjian, "Engineering analysis and numerical study on stability evaluation of seepage slope reinforcement stability of Yunmao expressway," *Front. Mater.*, vol. 10, no. October, pp. 1–18, 2023, doi: 10.3389/fmats.2023.1269175.

[16] B. Chairullah, M. Sungkar, R. P. Munirwan, K. Jamaluddin, F. F. Ramadhani, and R. P. Jaya, "The Investigation of Stability on Slopes Utilizing Reinforcement Gabion Walls and Concrete Piles for Mitigating Landslide Disasters," *Open Constr. Build. Technol. J.*, vol. 18, no. 1, pp. 1–9, 2024, doi: 10.2174/0118748368310059240605115115.