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Assessing the Impact of Mesh Density on Safety Factor in 2D and 3D Finite Element Modeling: A Case Study of Landslide Mitigation with Corrugated Concrete Sheet Pile (CCSP)

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ABSTRACT

The problem of landslides in irrigation canal embankments often occurs in areas with soft and expansive soils that have low bearing capacity and are easily changed in volume due to fluctuations in water content. One of the main triggers is the rapid drawdown phenomenon that causes a sudden decrease in slope stability. In this study, slope stability analysis was conducted using the finite element method with PLAXIS 2D and PLAXIS 3D software. The main objective of the study was to evaluate the effect of mesh variation and soil model selection between Mohr-Coulomb Undrained A and Hardening Soil on Safety Factor (SF) value and slope settlement pattern. The reinforcement treatment analyzed was the use of Corrugated Concrete Sheet Pile (CCSP) installed on the side of the slope to improve stability. The results showed that the mesh variation affected the SF results and stress distribution patterns, especially in the 3D model. The Hardening Soil model produced more realistic deformation and SF predictions than the Mohr-Coulomb model. Thus, choosing the right soil model and mesh configuration is very influential in producing accurate analysis and can be used as a reference in the design of irrigation canal slope treatment.

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1. INTRODUCTION

Irrigation infrastructure development often comes with complex geotechnical challenges, especially in areas with soft and expansive soil conditions. Soft soils have low bearing capacity and high long-term consolidation, which can result in excessive settlement and overlying embankments. Meanwhile, expansive soils expand when wet and shrink when dry, making them highly susceptible to cracking and structural deformation [1]. Irrigation canal slope collapse is often caused by a combination of slope geometry, embankment load, and groundwater level fluctuations. One of the primary triggers is the rapid drawdown phenomenon, which is a sudden drop in the water table that causes an imbalance in pore water pressure and a decrease in slope retaining force. This makes the slope unstable, particularly if it lacks an effective reinforcement system.

Handling embankment structures on soft soil requires an integrated approach that includes vertical reinforcement and subgrade improvement. One reinforcement method that is considered effective is the use of Corrugated Concrete Sheet Pile (CCSP), which functions to resist soil lateral forces and increase slope stability [2]. The use of a sheet pile retaining system can significantly improve slope safety, especially when combined with embankment materials that meet technical requirements.

The finite element method (FEM) is a reliable method for analyzing slope stability and evaluating the effectiveness of reinforcement systems and has been widely used in geotechnical studies. PLAXIS 2D and 3D are FEM-based software that can model soil response in two and three dimensions. The 3D model produces more representative results for complex geometries, but this is dependent on the mesh configuration used [3].

Numerical analysis with PLAXIS 2D and 3D utilizes a numerical discretization method that is essential in FEM by transforming complex geometry models of soils and structures into finite elements and applying appropriate constitutive models to describe the behavior of soil or rock [4]. FEM modeling can capture the influence of soil strength, pore water pressure, and other relevant parameters, allowing for the identification of safety factors and failure mechanisms [5]. FEM also employs a network of elements; in 2D analysis, triangular elements with 15 nodes are used, while 3D analysis employs a tetrahedral element network with 10 nodes. As a result, 3D analysis allows for more detailed stress distribution due to the greater number of interconnected nodes [6].

In addition to the numerical method, selecting the type of soil model significantly influences the analysis results. The Mohr-Coulomb Undrained A model is commonly used for a conservative approach, whereas the Hardening Soil model is more accurate in predicting plastic behavior and consolidation, especially for soft and intermediate soils [7].

The purpose of this study is to determine the effect of mesh variation and soil model on slope stability analysis of irrigation canals using PLAXIS 2D and 3D, and to assess the effectiveness of landslide mitigation using Corrugated Concrete Sheet Pile (CCSP). The findings are expected to serve as a technical reference for the design and management of embankment structures on soft soils prone to landslides.

2. LITERATURE REVIEW

A literature review provides an overview of previous studies and theories related to soil behavior, slope stability, and modeling approaches in geotechnical engineering. This section discusses three main topics: soft soil, landslides, and soil modeling using the Mohr-Coulomb criterion. The aim is to present the fundamental concepts and parameters that form the basis of the analysis in this research.

2.1 Soft Soil

The type and classification of soft soil are determined by its properties and characteristics, which include volume change, type and amount of mineral content, natural unit weight, variation in water content, soil density, loading conditions, soil structure, and time. Soft soil is recognized as one of the most problematic soil types in engineering applications. Its behavior is more complex compared to other soils. Classified soft soils into three types: silt, clay, and peat. Each of these types has different criteria. Silt and clay are most commonly analyzed to determine soil properties in geotechnical engineering. The criteria for soft clay soil include a shear angle (φ) of 14°–20°, undrained shear strength (Cu) of 25–50 kPa, unit weight (γ) of 14.2–15.8 kN/m^3, and compressibility index (Cc) ranging from 0.15–0.3.

2.2 *Landslides*

A landslide is defined as the downslope movement of slope-forming materials, such as rock, soil, debris, or a combination of these materials. The process of landslide occurrence can be explained as follows: water infiltrating into the soil increases the soil weight. When the water reaches an impermeable layer acting as a slip surface, the soil becomes slippery, and the overlying weathered soil mass will move downslope and eventually slide out of the slope. A landslide occurs when the driving force acting on a slope exceeds the resisting force. The resisting force is generally influenced by the strength of the rock mass and soil density, whereas the driving force is affected by slope angle, water content, external load, and the unit weight of the soil and rock.

2.3 *Soil Modeling with Mohr-Coulomb*

In 1773, Coulomb introduced the concept of earth pressure on retaining walls, which later became known as the Mohr-Coulomb failure criterion. This model assumes soil behaves as a linear elastic–perfectly plastic material, without hardening or softening. The failure criterion is expressed as:

$$\tau_f = \sigma'_{nf}\, tan\emptyset' + c'$$

where τf′ and σnf′ are the shear and effective normal stresses at failure.

3. METHODS

This study uses a comprehensive Finite Element Method (FEM), utilizing PLAXIS 2D and 3D, to soil. This methodology includes three levels of mesh density (coarse, medium, fine), two advanced soil constitutive models (MC-A and HS-A), and two reinforcement conditions (with and without CCSP), systematically evaluating their effects on safety factors and failure mechanisms for representative channel geometries. The research methodology comprises the following stages:

1. Define geometry of the irrigation canal and embankment on soft soil.
2. Assign material properties:
   - For each soil layer using MC-A and HS-A models
   - or CCSP as reinforcement material
3. Apply boundary conditions and initial water level to simulate typical operating condition
4. Set up mesh variation: Generate coarse, medium, and fine mesh configurations.
5. Run simulations in PLAXIS 2D and 3D for each mesh and soil model scenario, both with and without CCSP
6. Extract results:
   - Safety Factor (SF)
   - Displacement and stress distribution
   - Failure mechanism
7. Compare results and analyze the effect of:
   - Mesh quality
   - Soil model selection
   - CCSP reinforcement presence
8. Interpret findings and provide recommendations for soft soil slope reinforcement design.
9. Specimen and Input Data:
   - Soil specimen: Soft clay with lab data or SPT-derived parameters.
   - Geometrical dimensions: Based on actual irrigation canal cross-section.
   - CCSP specification: Modeled as linear elastic

material with high stiffness and moment resistance.

10. Tools and Software: PLAXIS 2D and PLAXIS 3D: For FEM analysis.
11. Testing and Data Acquisition:
    - FEM simulations are treated as virtual experiments where mesh quality, soil models, and reinforcement presence are independent variables.
    - Data acquired includes: Safety Factor (SF) using strength reduction method, Plastic points distribution and failure surface pattern.

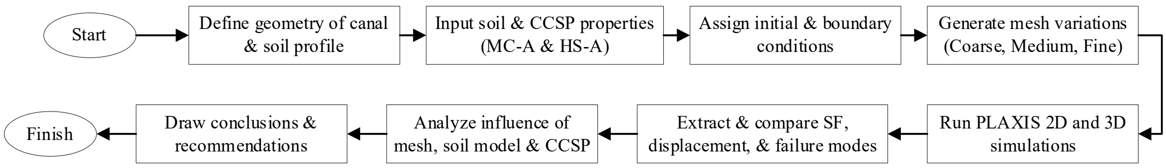

Figure 1. Flowchart

4. RESULTS AND DISCUSSION

In the analysis of soft soil behavior with a Plasticity Index (PI) of 46.17, which is classified as high-permeability soil, two modeling approaches are compared: Mohr-Coulomb and Hardening Soil (Undrained A). The soil parameters applied in the models are presented in **Table 1**, while the configuration of the soil layers is illustrated in **Figure 2**. Parameter calibration, particularly of the shear strength value, is conducted through slope stability analysis in order to highlight the significance of enhancing soil shear strength in addressing the key challenges associated with soft soils.

Table 1. Soil Parameter

Parameter	Name	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5	
Material Model	Model	MC	MC	MC	MC	MC	-
Types of Material	Type	U-A	U-A	U-A	U-A	U-A	-
Dry Unit Weight	γ_{unsat}	15,495	15,789	15,691	14,808	18,535	kN/m³
Wet Unit Weight	γ_{sat}	16,524	16,407	16,789	15,936	19,000	kN/m³
Modulus Young	E′	2400	3206	7500	9375	14725	kN/m²
Poisson Ratio	v	0,2	0,2		0,2	0,4	-
Cohesi (*constant*)	C′ref	3,70	3,75	22,0	22,0	1,50	kN/m²
Shear Angle	Ø′	18,0	20,98	34,0	34,0	21,63	°
Material Model	Model	HS	HS	HS	HS	HS	-
Reference secant stiffness	E_{50}^{ref}	2400	3206	7500	9375	14718,25	kN/m²
Reference tangent stiffness	E_{oed}^{ref}	2400	3206	7500	9375	14718,25	kN/m²
Reference stiffness	E_{ur}^{ref}	7200	9619	22500	28125	44154,75	kN/m²
Angka Poisson	v_{ur}	0,2	0,2	0,2	0,2	0,2	-
Power exponent	m	0,5	0,5	0,5	0,5	0,5	-
Horizontal Pressure	K_0	0,938	0,945	0,925	0,919	0,364	-
Failure Ratio	Rf	0,9	0,9	0,9	0,9	0,9	-
Reference stiffness stress	p^{ref}	100	100	100	100	100	kN/m²

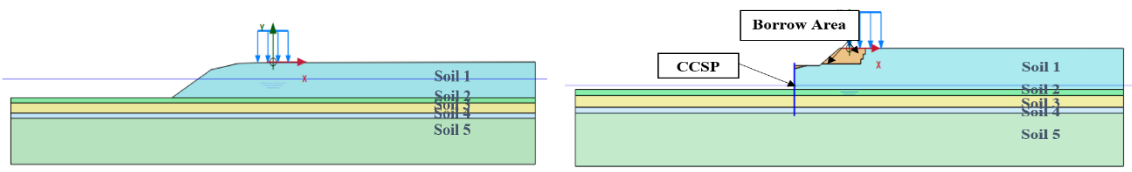

Figure 2. Soil Layer

The numerical analysis started after the slope geometry was discretized into smaller, more manageable interconnected elements, known as meshing. Each finite element in the mesh is assigned a set of equations that describe its behavior under loading and boundary conditions. By solving and combining these equations for each element, the overall behavior of the slope can be determined. The element distributions for the connectivity plots, based on five different levels of network roughness values for both 2D and 3D FEM, are shown in **Table 2**. It is indicated that smoother surfaces result in a higher density of node points. Furthermore, the number of node points is influenced by the generated element size, with larger element sizes leading to a reduced number of nodes within the structure.

Table 2. Number of Elements Distribution for Different Mesh

Initial	**2D FEM**	**Size Node (m)**	**3D FEM**	**Size Node (m)**
Very Coarse	9703	1.827	842	9.805
Coarse	10675	1.733	1408	7.599
Medium	12649	1.649	3048	5.389
Fine	15991	1.432	6277	4.008
Very Fine	19711	1.3	11812	3.115
CCSP	**2D FEM**	**Size Node (m)**	**3D FEM**	**Size Node (m)**
Very Coarse	9843	1.726	1507	6.689
Coarse	10457	1.656	2447	5.503
Medium	11683	1.613	3889	4.635
Fine	14051	1.483	7201	3.687
Very Fine	18025	1.304	13763	2.899

Meanwhile, **Figure 3** displays the critical shear surfaces generated on the connectivity plot for 2D and 3D FEM analysis. The critical shear surface in the modeling can show how the soil mass will initiate and propagate shear motion in response to external forces (gravity).

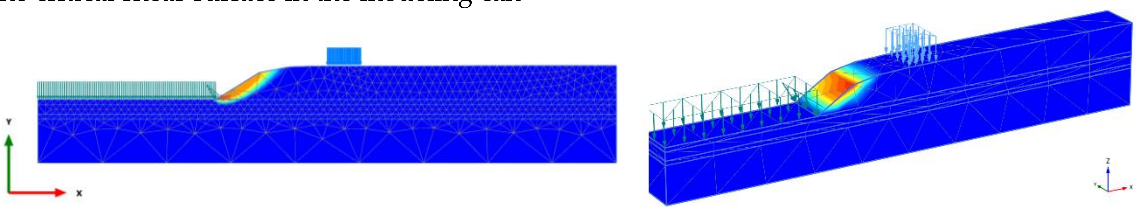

Figure 3. Critical Slip Surface Initial Plan in 2D & 3D FEM

The analysis shows in **Figure 4** that mesh variation affects the safety factor (SF) value differently depending on the model dimensions and soil type used. In the 2D model, changing from very coarse to very fine meshes results in relatively stable SF values with small differences between them. However, in the 3D model, the SF values showed more significant variations, with coarse and medium meshes giving higher SF values than very fine meshes. This indicates that the finer mesh in the 3D model is able to capture soil stability conditions more accurately and conservatively, whereas the coarse mesh overestimates the safety factor due to resolution limitations.

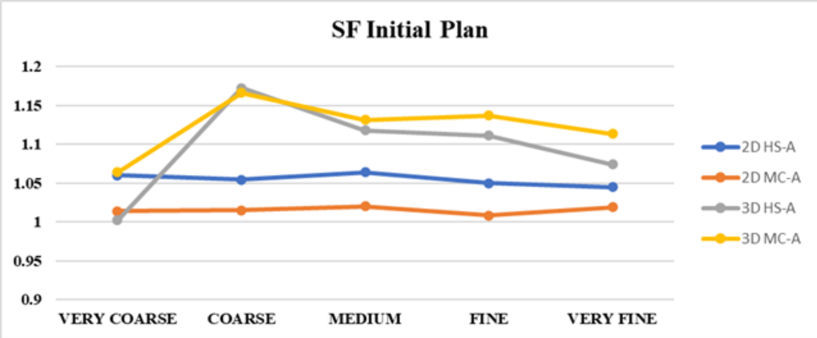

Figure 4. The Effect of Mesh Variation on Safety Factors in Initial Plans

Moreover, the 3D models typically generate higher safety factors (SF) across coarse to fine meshes when compared to the 2D models. The very coarse mesh in the HS-A soil type is an exception to this pattern, producing a lower SF [8]. Alongside the 3D models overall superiority, as shown in **Figure 5**, there is a visible decrease in SF as mesh variation increases. In particular, **Figure 6** shows that regardless of the dimensionality, the SF values drop as the mesh is changed. This steady decrease is explained by the enhanced capacity of finer or more suitably varied meshes to more precisely capture localized stress concentrations and deformation patterns, resulting in a less conservative stability evaluation. These findings thus highlight how crucial it is to use 3D models, which by their very nature take into consideration intricate spatial relationships and boundary effects, in order to get a more accurate and less mesh-dependent depiction of slope stability or soil structure behavior, especially when evaluating critical scenarios. While the difference between HS-A and MC-A soil types is small, soil type still has an impact on SF values, with HS-A giving slightly higher SF in the 2D model and MC-A showing slightly higher SF values in the 3D model. Coarser networks produce higher SF values than finer networks. In theory, the fewer nodes generated will have a faster computation time for analysis. On the other hand, increasing the number of elements and nodes yields SF values that are generally more conservative than those obtained with fewer elements and nodes [9].

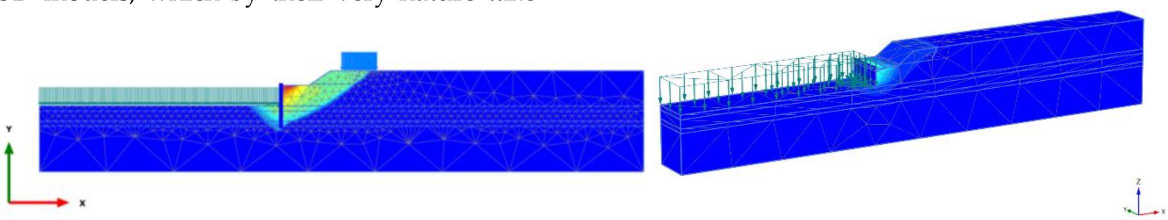

Figure 5. Critical Slip Surface Reinforcement with CCSP in 2D & 3D FEM

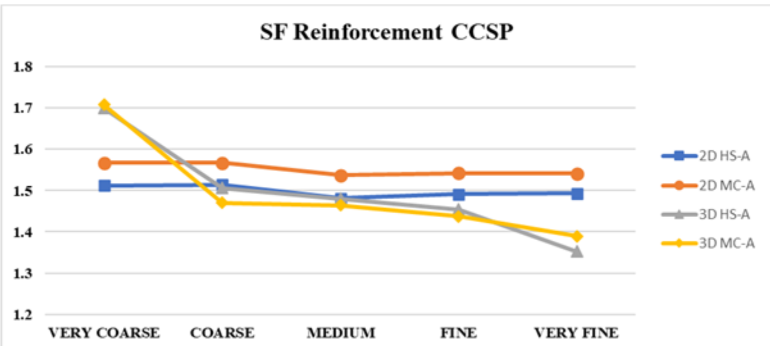

Figure 6. The Effect of Mesh Variation on Safety Factors in Reinforcement with CCSP

Based on these investigations, it is recommended to use a medium or fine mesh in 3D modeling to achieve reasonably accurate and conservative results. A very fine mesh in the 3D model produces slightly lower SF values, which can be considered more conservative, but additional convergence analysis is required to ensure its stability. In conclusion, mesh selection and model dimensions have a significant impact on the safety factor analysis results, so they should be carefully considered based on the modeling needs and purpose.

A comparison of the safety factor (SF) values in the 2D and 3D models indicates a significant percentage difference depending on mesh size and soil type. In the HS-A soil type, the 3D model reduced SF by approximately 5.47% in the very coarse mesh when compared to the 2D model. However, for finer mesh sizes, the 3D model increases SF by 2.75% to 11.19% compared to the 2D model. In contrast, in the MC-A soil type, the 3D model consistently provides higher SF values than the 2D model, with percentage increases ranging from 4.93% in the very coarse mesh to 14.78% in the coarse mesh. This suggests that using 3D models produces more conservative and realistic results, especially for medium to fine mesh sizes, whereas 2D models may fail to capture the complexities of real soil and slope stability.

5. CONCLUSION

The study clearly demonstrates that mesh variation and model dimensionality significantly influence the safety factor (SF) in slope stability analysis. In 2D models, changes in mesh size have a relatively minor effect on SF values, while in 3D models, finer meshes capture the soil behavior more accurately, resulting in lower and more conservative SF values. This highlights the superior capability of 3D models in accounting for complex spatial interactions and boundary conditions.

Although coarser meshes tend to produce higher SF values due to lower resolution and faster computation, they may lead to overestimations of slope stability. Conversely, finer meshes increase computational effort but yield more realistic and reliable outcomes. Among the two soil types examined, HS-A shows slightly higher SF values in 2D analysis, while MC-A performs better in 3D scenarios.

Ultimately, medium to fine mesh sizes in 3D models are recommended to achieve a balance between accuracy and computational efficiency. These configurations provide a more conservative assessment of slope stability, crucial for safety-critical geotechnical designs. The results support the adoption of 3D modeling as a more reliable approach, especially when dealing with complex terrain and critical loading conditions.

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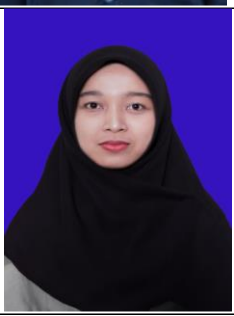	**Fuji Asema** I completed my undergraduate studies in Civil Engineering at Universitas Negeri Padang, graduating in 2018, and continued my Master’s degree in Civil Engineering at Universitas Andalas in 2020. My area of expertise is geotechnical engineering, with a strong research interest in liquefaction, foundation design, and soil properties. I can be contacted via email at fuji.asema@polinema.ac.id

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