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Effect of Mesh Coarseness on Slope Stability Analysis Using 2D and 3D Finite Element Method

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ABSTRACT

A comprehensive understanding of slope stability is essential for ensuring the safety and durability of structures built on or near slopes and mitigating the risks associated with landslides and slope failures. Slope stability is typically evaluated using the factor of safety (FOS) based on the critical slip surfaces. The calculation of FOS is commonly executed using Limit Equilibrium Method (LEM) by dividing the slope into several vertical slices. However, the stability analyses using Finite Element Method (FEM) have gained significant attention in geotechnical engineering due to their ability to simulate slope behaviour and predict stability accurately by employing mathematical models and computational algorithms. Hence, this paper aims to analyse the FOS of the unreinforced slope using 2D FEM and 3D FEM conducted through computer software while examining the influence of different mesh coarseness. Besides that, the formation of critical slip surfaces and the displacement behaviour of the slope are also presented. A slope geometry model was analysed using PLAXIS 2D and PLAXIS 3D with different mesh coarseness. The findings were compared and discussed. The findings reveal that the values of FOS generated by 3D FEM are slightly larger compared to 2D FEM analysis, ranging from 1.27% to 2.56%. On the other hand, the effect of mesh coarseness indicates that coarser mesh sizes yield higher FOS values compared to finer mesh sizes. The shape, location and depth of the critical slip surfaces are consistent for each analysis in both methods. However, the maximum displacement values differ for each mesh coarseness, as the locations of maximum total displacement are identified at different nodes due to varying numbers of elements but still within the same potential failure zone. Overall, this comparative study is crucial in ensuring the validity of the performed analyses. Understanding the capabilities and limitations of 2D and 3D numerical analyses to achieve reliable and accurate results is important to balance mesh coarseness and computational efficiency.

Keywords: Slope stability; Critical slip surface; Finite element method; Mesh coarseness

INTRODUCTION

Slope stability is a critically important issue in Malaysia due to frequent landslides in recent years. Unstable slopes contribute to landslide events, compounded by adverse weather conditions and increased rainfall intensity. Additionally, the characteristics of soil shear strength play a significant role in slope stability. Slope stability refers to the ability of a slope to resist failure and maintain its stability under the influence of various forces, such as gravity, water pressure, and seismic activities. Understanding slope stability is essential for ensuring the safety and durability of structures built on or near slopes and mitigating the risks associated with landslides and slope failures. Slope stability is evaluated using the Factor of Safety (FOS) value. According to the Public Work Department of Malaysia, the minimum global FOS for unreinforced slopes is 1.3, as stated in Guidelines for Slope Design (PWD 2010).

Traditionally, the FOS is analysed manually or by computer software using the limit equilibrium method (LEM). However, stability analyses using Finite Element Method (FEM) in geotechnical engineering have gained significant attention and are widely used to obtain more detailed and precise analyses. Schweiger et al. (2019) reviewed the examples of successful numerical analysis in geotechnical engineering complex problems to prove that numerical analysis has emerged as a powerful tool for assessing slope stability. By employing mathematical models and computational algorithms, engineers can simulate the behaviour of slopes and predict their stability more accurately and efficiently than traditional methods. Moreover, Augarde et al. (2021) highlighted that numerical analysis allows for the consideration of complex factors and boundary conditions, facilitating a comprehensive understanding of the underlying mechanisms that govern slope stability.

Furthermore, advancements in technology and computer software have significantly impacted the field of geotechnical engineering, enabling 2D FEM and 3D FEM analyses using software such as PLAXIS. According to Hemeda (2022), PLAXIS is a well-established computer software program with significant recognition for its ability to analyse complex engineering tasks using mathematical models and computational algorithms. Initially developed at the Technical University of Delft, Netherlands, in the 1970s, Plaxis is now part of Bentley Systems, a global software development company specialising in infrastructure engineering software. PLAXIS has several packages, including PLAXIS 2D to model in two-dimensional and PLAXIS 3D to analyse in a three-dimensional context (Plaxis 2D, 2020; Plaxis 3D, 2020).

In 2D numerical analysis, engineers simplify the slope geometry by assuming it to be infinitely long in one direction, typically along the slope's longitudinal axis. This simplification allows for significant reductions in computational effort while capturing the essential features and mechanisms that control slope behaviour. On the other hand, the 3D numerical analysis offers a more realistic representation of the slope by considering all three dimensions, accounting for irregular geometries, spatial variations, and the influence of adjacent structures or geological features that Kumar et al. (2023) have described.

Mohamed et al. (2022) further explained that 2D and 3D numerical analysis methods involve discretising the slope into finite elements and applying appropriate constitutive models to describe the soil or rock behaviour. These models can capture the effects of soil strength, pore water pressures, and other relevant parameters to simulate the slope response under different loading and environmental conditions. By analysing the equilibrium and deformation characteristics of the slope, numerical models can assess factors of safety, identify potential failure mechanisms, and aid in the design of effective stabilisation measures. Furthermore, 2D analysis was conducted using 15-noded triangular elements to achieve higher accuracy in the numerical calculations, while 3D analysis utilised a mesh of 10-noded tetrahedral elements. As a result, the 3D analysis employed more distributed elements than the 2D analysis, enabling a more detailed representation of slope behaviour and facilitating the analysis of potential failure mechanisms.

Moreover, mesh generation is essential in representing the slope geometry and discretising it into smaller and interconnected elements to perform finite element calculation, as explained in the PLAXIS manual (Plaxis 2D, 2020; Plaxis 3D, 2020). Each finite element within the mesh has a defined shape and size. The mesh captures the geometric details of the slope structure being analysed. Moni and Sazzad (2015) investigated the influence of mesh size from fine to coarse. The results indicated that finer mesh provided a more conservative FOS than coarser mesh. The FOS value was also observed to decrease further when the slope geometry was divided into more elements. These findings are also consistent with those presented in the research paper by Lin et al. (2020), which analyzed slopes using 2D and 3D FEM. Models with higher mesh density yielded lower FOS values, with a percentage error between FOS values of 18% for coarse and very fine mesh sizes. Valentino (2023) conducted FEM modelling of weak soil layers in slope stability analysis and found that increasing the number of elements and nodes allows the generation of critical FOS values compared to those obtained with fewer elements and nodes. Therefore, this study examines the effect of mesh coarseness on the FOS value of the unreinforced slope. Besides that, the formation of critical slip surfaces and the displacement behaviour of the slope due to the different mesh coarseness are also presented and discussed. By understanding the capabilities and limitations of 2D and 3D numerical analyses, engineers can make accurate decisions in slope stability design and reduce risk in geotechnical engineering projects.

METHODOLOGY

SOIL PROPERTIES AND GEOMETRIC MODEL

Table 1 shows the properties of residual soil for the slope area located at Taman Bukit Ampang, Selangor, Malaysia. Those parameters, namely the unit weight of soil (γ), angle of friction (ϕ^{o}), cohesion (c), poison ratio (v) and modulus young (E), are the input for the calculation of 2D FEM and 3D FEM. The parameters were extracted from the soil investigation report based on the laboratory test conducted according to BS1377: Part 2 to determine the physical properties and BS1378: Part 8 to obtain the shear strength parameter of soil at the slope area (BSI 1990).

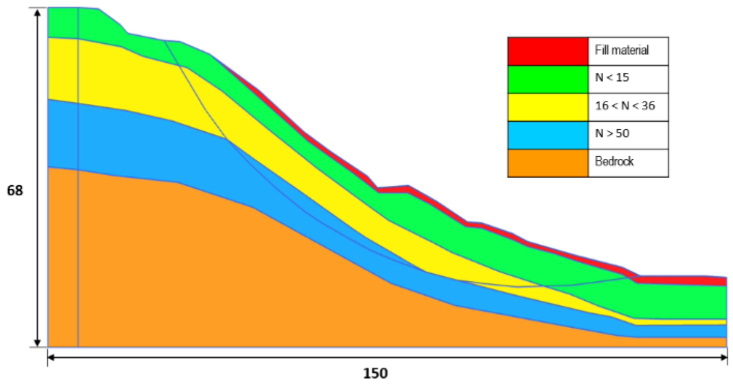
According to the Geological Map of Peninsular Malaysia, the entire study area is underlain by granite rock

Triassic Age. The formed granite consists predominantly of light grey, coarse to medium-grained biotite granite (Saim et al., 2023).

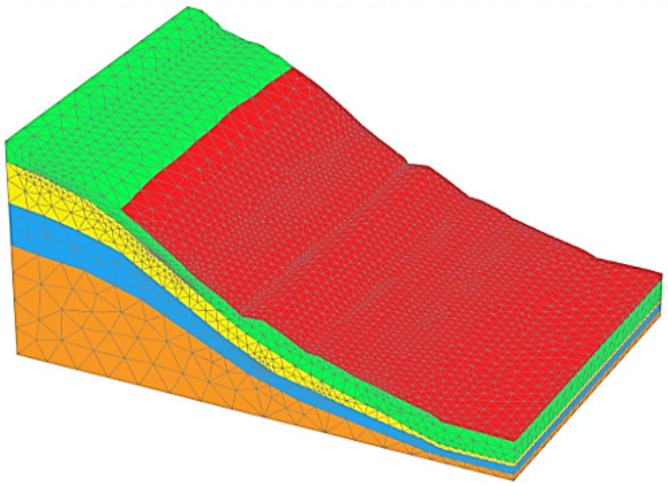
The fill material is composed of silty SAND from the ground surface to 1.50 m depth. Then, the following layers consist of stiff sandy SILT (SPT-N < 15), very stiff sandy SILT (16 < SPT-N < 36), hard sandy SILT (SPT-N > 50) and bedrock consisting of medium strong slightly weathered granite with RQD 80% - 94%. In this study, a slope cross-section was involved, and the slope stability of existing slopes was analysed without any reinforcement applied to the slope. Figures 1 (a) and (b) show the slope geometry profile in 2D and 3D modelling, respectively.

TABLE 1. Soil parameter

Soil type	γ (kN/m^3)	ϕ (°)	c (kPa)	ν	*E* (MPa)
Layer 1 (Fill material)	15	31	3	0.310	20
Layer 2 (N<15)	15	34	5	0.341	20
Layer 3 (16<N<36)	15.5	34	5	0.341	50
Layer 4 (N>50)	16	35	6	0.341	100
Layer 5 (Bedrock)	24	45	100	0.200	1000



(a) 2D model



(b) 3D model

FIGURE 1. Slope geometry models (a) 2D model (b) 3D model

SLOPE STABILITY ANALYSIS

This study used the computer software PLAXIS 2D and PLAXIS 3D to perform FEM analyses. The software then performs FEM-based analysis and generates comprehensive results, including displacements and factors of safety.

In 2D analyses, the plane strain model was employed with 15 nodded triangular elements for higher accuracy in the numerical calculation. For 3D analyses, the soil formations are modelled by 10 nodes of tetrahedral mesh elements. The Mohr-Coulomb model (MC) was employed to analyse the soil material behaviour due to its well-established history in slope stability analysis (Salih 2021; Sazzad et al. 2016; Sungkar et al. 2020). It is widely used in geotechnical engineering as it does not require complex parameters. Besides that, this model can be applied to different soil types, including coarse-grained soils, fine-grained soils, and their mixtures.

The initiation of the finite element calculation involved the generation of a mesh after the complete definition of the geometry model and assigning material properties to all layers. In this study, the 2D and 3D methods generated five different global mesh, namely very coarse, coarse, medium, fine, and very fine, to investigate the effect of mesh coarseness on slope stability and critical slip surfaces.

In PLAXIS, the strength reduction (phi/ c reduction) approach is employed to calculate the factor of safety in slope stability analysis. This method involves gradually reducing the shear strength parameters of the soils, such as the angle of internal friction (ϕ) and cohesion (c) until failure occurs. The shear strength values of soil parameters required for the computation of safety factors are determined using a total multiplier, ΣMsf, as stated in Equation (1) based on the PLAXIS manual (Plaxis 2D, 2020; Plaxis 3D, 2020).

$$\Sigma Msf = \frac{\tan \phi_{input}}{\tan \phi_{reduced}} = \frac{c_{input}}{c_{reduced}} \qquad (1)$$

The strength parameters denoted by the subscript ‘input’ represent the properties initially specified in the material sets, and the parameters labelled with the subscript ‘reduced’ correspond to the adjusted values employed in the analysis. At the beginning of the calculation, ΣMsf is set to 1.0 to ensure that all material strengths are initially set to their input values. By iteratively decreasing the shear strength parameters, the strength reduction approach allows for the evaluation of the factor of safety and the identification of potential failure conditions in the analysed slope. A Safety calculation is performed using the load advancement number of steps procedure. The calculation will be repeated with a larger number of steps until the failure mechanism fully develops. The principal results of FOS calculation are the failure mechanism and the corresponding ΣMsf, as written in Equation (2) by referring to the PLAXIS manual.

$$\begin{aligned} FOS &= \frac{Available\ strength}{Strength\ at\ failure} \\ &= value\ of\ \Sigma Msf\ at\ failure \end{aligned} \qquad (2)$$

RESULTS AND DISCUSSION

CRITICAL SLIP SURFACE AND FACTOR OF SAFETY (FOS)

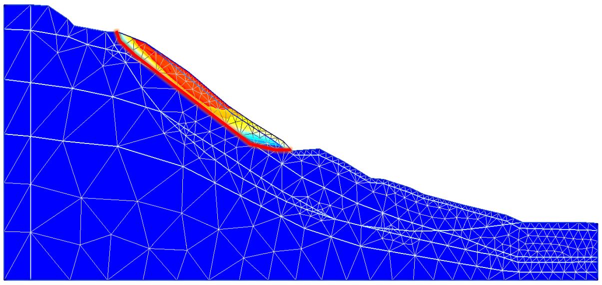
The numerical analysis proceeded once the slope geometry was discretised into smaller, more manageable interconnected elements, known as meshing. Each finite element within the mesh is associated with a set of equations that describe its behaviour under loading and boundary conditions. By solving these equations for each element and combining them, the overall behaviour of the slope can be determined.

Table 2 shows the element distribution for the connectivity plot based on five different mesh coarseness for 2D FEM and 3D FEM. As depicted, finer mesh divided the slope geometry into smaller sizes, requiring higher element distribution numbers.

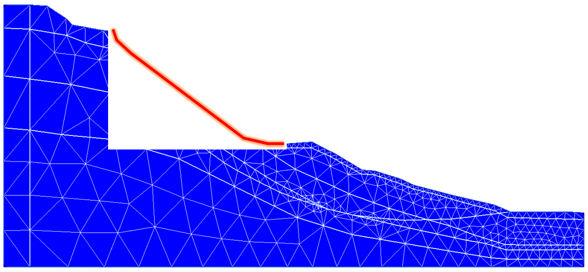
Meanwhile, Figure 2 (a – e) presents the critical slip surfaces generated on the connectivity plot for 2D FEM analyses. Meanwhile, the 3D FEM critical slip surfaces are shown in Figure 3 (a - e). The critical slip surfaces represent the path or zone along which the soil mass is most susceptible to initiating and propagating a sliding movement under external forces, such as gravity, as indicated by the different shading on the slope surface. It can be observed that various mesh coarseness results in the consistent formation of critical slip surfaces in terms of the location, the shape of slope portions involved and the expected depth of failure occurrence. However, in 2D FEM, slight differences can be noticed in determining the most critical sections based on the red-coloured shading, where the very coarse mesh indicates a smaller coverage of the most critical area compared to other mesh coarseness levels.

TABLE 2. Numbers of elements distribution for different mesh coarseness for 2D FEM and 3D FEM

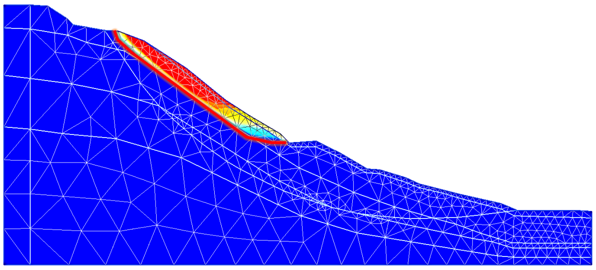
Method	2D	3D
Element distribution	Numbers of Elements	
Very coarse	800	75233
Coarse	859	75291
Medium	897	76124
Fine	1037	78951
Very fine	1251	87897



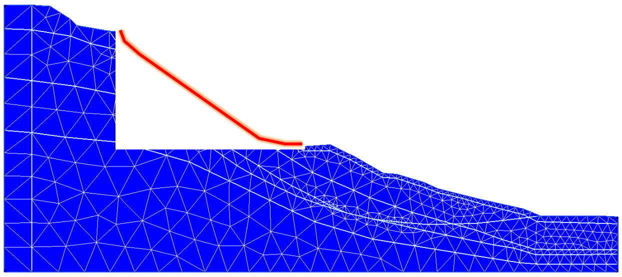
(a) Critical slip surface: Very coarse mesh (2D FEM) – 800 elements



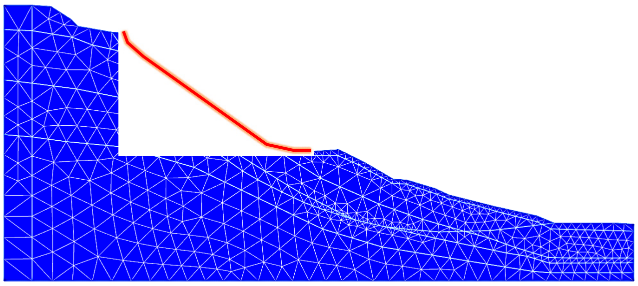
(b) Critical slip surface: Coarse mesh (2D FEM) - 859 elements



(c) Critical slip surface: Medium mesh (2D FEM) – 897 elements

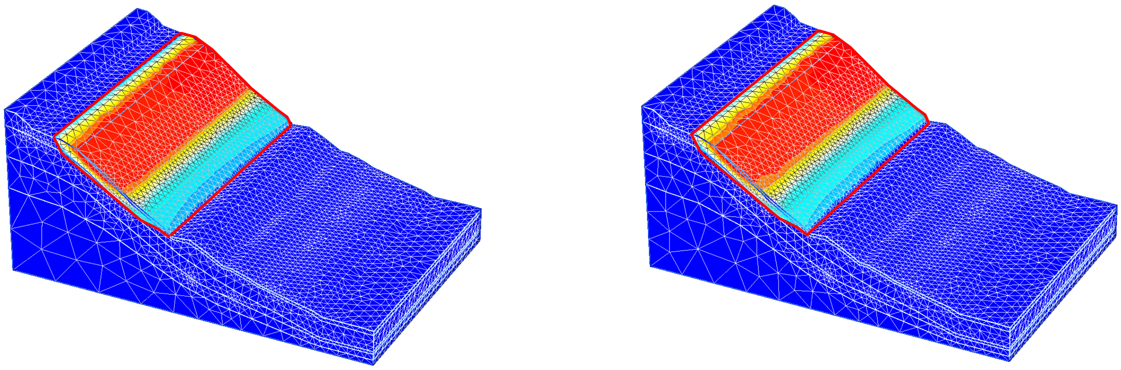


(d) Critical slip surface: Fine mesh (2D FEM) – 1037 elements



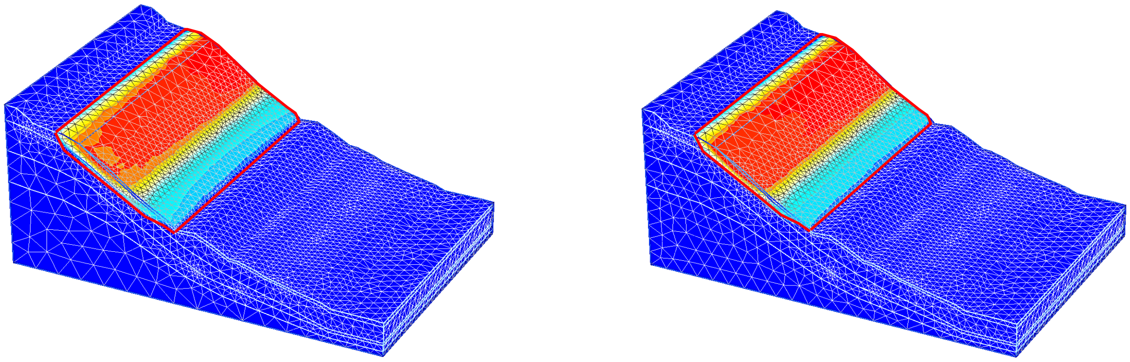
(e) Critical slip surface: Vey fine mesh (2D FEM) – 1251 elements

FIGURE 2. Critical slip surface generated by 2D FEM for different mesh coarseness



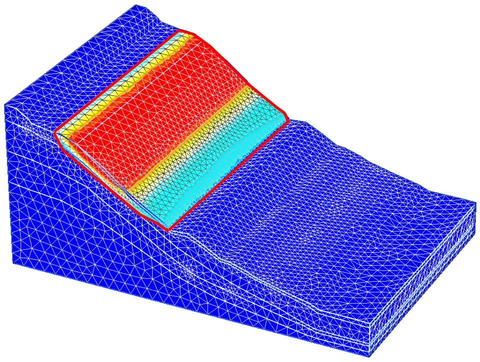
(a) Very coarse mesh (3D FEM) – 75233 elements

(b) Course mesh (3D FEM) – 75291 elements



(c) Medium mesh (3D FEM) – 76124 elements

(d) Fine mesh (3D FEM) – 78951 elements



(e) Very fine mesh (3D FEM) – 87897 elements

FIGURE 3. Critical slip surface generated by 3D FEM for different mesh coarseness

Furthermore, Table 3 illustrates the FOS values generated from the 2D and 3D numerical computations conducted by the utilised software. It can be observed that the resulting FOS values from 2D FEM and 3D FEM are slightly different for each mesh coarseness size. The percentage error in FOS values between the two is within the range of 1.69% to 2.56%. The 3D FEM calculation produced slightly higher FOS values compared to those obtained from the 2D analyses. The trends agree with the finding reported by Mohamed et al. (2022) and a study conducted by Liu Jie-Qun and Liu Jin-Long (2012).

TABLE 3. FOS value generated from numerical computations by PLAXIS 2D and PLAXIS 3D.

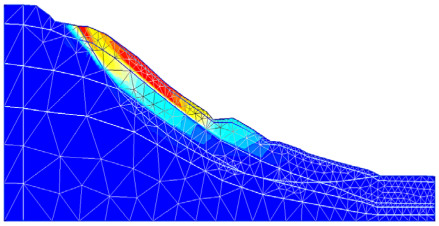
Mesh Coarseness	2D FEM FOS	3D FEM FOS	% Error with 2D FEM
Very coarse	1.18	1.21	2.54
Coarse	1.18	1.20	1.69
Medium	1.17	1.20	2.56
Fine	1.15	1.17	1.74
Very fine	1.14	1.16	1.75

In addition, the generated computations show that the trend of FOS values is decreasing as the finer mesh coarseness is specified during the numerical calculations. These findings are consistent with Moni and Sazzad (2015) and Lin et al. (2020). The coarser mesh produces a higher value of FOS than the finer mesh. Generally, a coarser mesh reduces the computational effort and time required for analysis. However, a coarse mesh oversimplifies the slope geometry and behaviour, leading to less accurate FOS results (Liu et al., 2020). Meanwhile, increasing the number of elements and nodes allows the generation of critical FOS values that are generally more conservative compared to those obtained with a lower number of elements and nodes (Valentino, 2023). Finer mesh captures the localised variations in stress and deformation more effectively, leading to more precise FOS calculations since the geometry is divided into smaller sizes of elements.

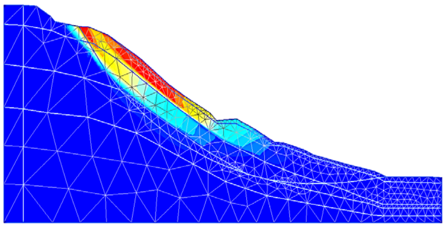
DEFORMATION

Subsequently, the analyses refer to the total displacement from the deformation mesh diagrams depicted in Figures 4 (a – e) and Figures 5 (a – e) by the 2D and 3D numerical computation.

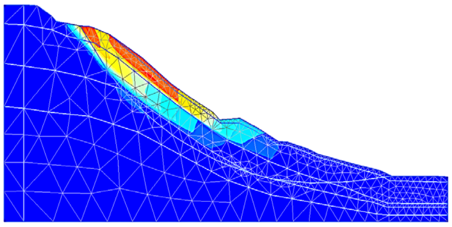
The total displacements displayed on a plot geometry are presented as shading that contains the magnitude of accumulated displacements at the end of the calculation step. The different shading indicates the different magnitude from the lowest displacement area to the higher displacement area. The plots are scaled up to 5000 times for 2D analyses and 2000 to 50000 times for 3D analyses to make the deformations more visible since the actual displacements might be very small and difficult to observe in their true scale.



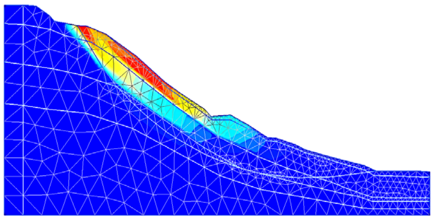
(a) Very coarse mesh Maximum displacement = 7.969 x 10^{-4} m (Element 273 at node 610)



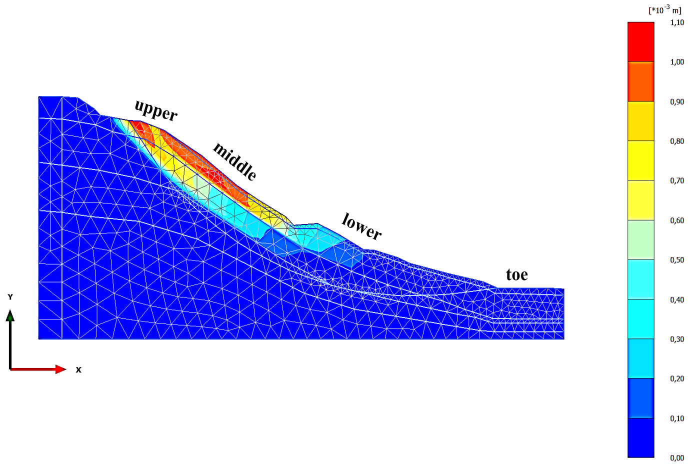
(b) Coarse mesh Maximum displacement = 8.89 x 10^{-4} m (Element 298 at node 860)



(c) Medium mesh Maximum displacement = 1.013 x 10^{-3} m (Element 280 at node 941)

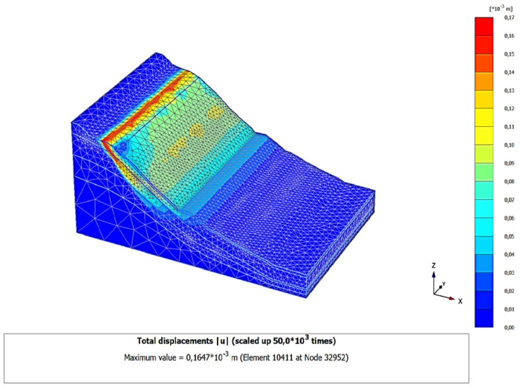


(d) Fine mesh Maximum displacement = 0.9524 x 10^{-3} m (Element 351 at node 285)

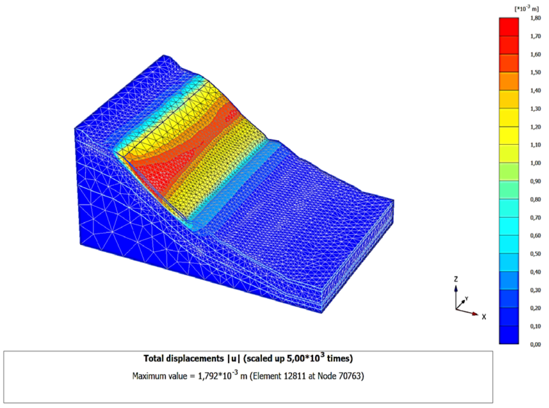


(e) Very fine mesh Maximum displacement = 1.040 x 10^{-3} m (Element 402 at node 712)

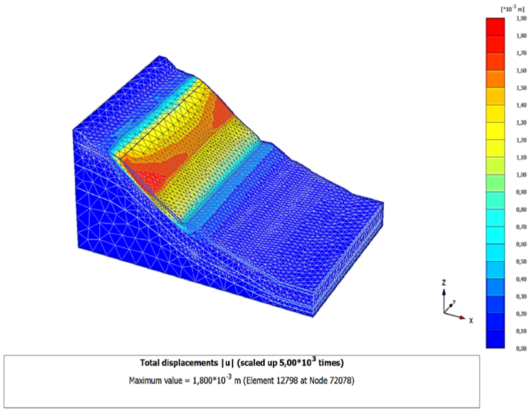
FIGURE 4. Total displacement by 2D FEM (scaled up 5000 times)



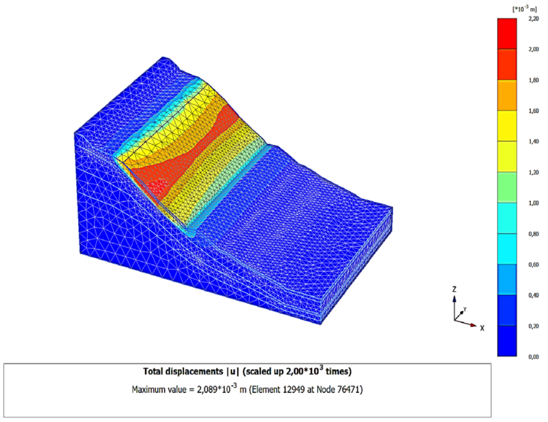
(a) Very coarse mesh Maximum displacement = 0.1647 x 10^{-3} m (Element 10411 at node 32952)



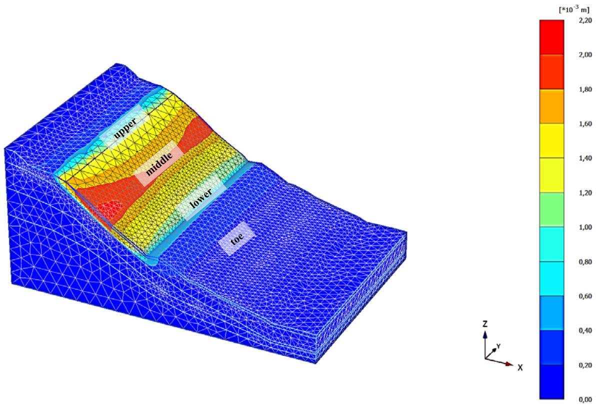
(b) Coarse mesh Maximum displacement = 1.792 x 10^{-3} m (Element 12811 at node 70763)



(c) Medium mesh Maximum displacement = 1.800 x 10^{-3} m (Element 12798 at node 72078)



(d) Fine mesh Maximum displacement = 2.089 x 10^{-3} m (Element 12949 at node 76471)



(e) Very fine mesh Maximum displacement = 2.226 x 10^{-3} m (Element 13548 at node 89167)

FIGURE 5. Total displacement by 3D FEM (scaled up 2000 to 50000 times)

As shown in Figures 4 and 5, the red shading identifies the areas of higher displacement that lead to critical potential failure zones. The results of the 2D FEM computations shown in Figure 4 indicate that all plots of total displacement exhibit the same shading pattern for all mesh coarseness. The critical displacement is concentrated in the middle section of the slope and partly in the upper section. The magnitude of displacement decreases as it moves towards the lower section, and no displacement is detected at the toe of the slope.

However, the displacement pattern by 3D FEM varies slightly for each mesh coarseness, as shown in Figure 5. In the case of a very coarse mesh, the location of the red shading only encompassed the upper section of the slope. It calculated a lower magnitude of maximum displacement compared to the other mesh coarseness. Meanwhile, the critical displacement generated due to coarse, medium, fine, and very fine mesh coarseness is concentrated in the middle section of the slope. Furthermore, from the fine and very fine mesh coarseness, it was observed that in the lower section of the slope, the area of displacement occurrence becomes progressively smaller compared to other mesh coarseness.

Meanwhile, variations were observed among different mesh coarseness in both 2D FEM and 3D FEM for the maximum displacement values obtained. This disparity arises from the different displacement locations for varying numbers of elements determined by the designated mesh coarseness during calculations. Figures 2 and 3 illustrate that the number of elements is higher when finer mesh coarseness is employed. Consequently, in Figures 4 and 5, distinct element and node configurations for maximum displacement were identified within the same potential failure zone.

Figure 6 illustrates the comparison of maximum displacement values generated by both methods. It is evident that overall, the 3D FEM produces more extensive maximum displacement compared to the 2D FEM.

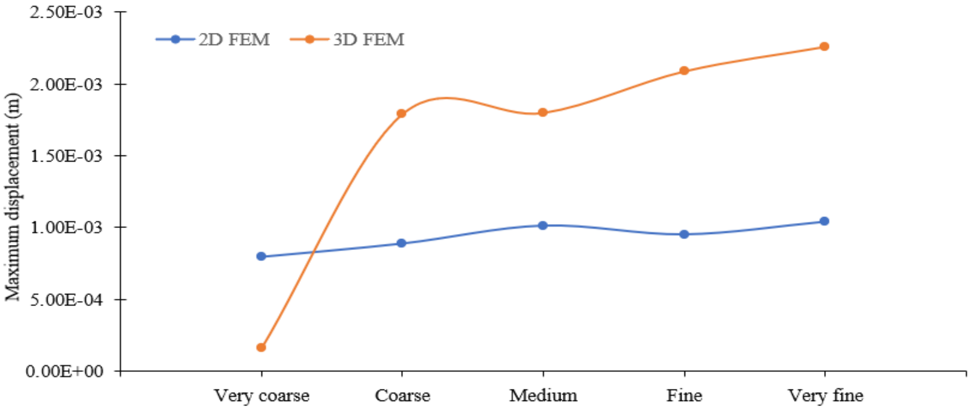


FIGURE 6. Distribution of maximum displacement by 2D FEM and 3D FEM

The difference in maximum displacement generated by 2D and 3D FEM analyses, as discussed by Jeramic (2000), is basically due to the limitation of 2D that considers only two dimensions (plain strain). This only partially captures the entire three-dimensional behaviour of the geometric system, which slopes fundamentally 3D in nature. Thus, 2D provides a more conservative FOS and displacement value than 3D FEM (Lu et al., 2013; Nasiri & Hajiazizi, 2020). On the other hand, the 3D analysis accounts for the entire spatial distribution of forces and displacements, providing a more comprehensive representation of the problem.

Besides that, the different displacement pattern in 3D is also due to the shear localisation that is better captured in 3D than in 2D. Shear localisation refers to the phenomenon where shear stresses accumulate in specific areas within the slope. This occurs when certain regions of the slope experience more significant displacements than others. The different displacements between 3D and 2D are attributed to the enhanced ability of 3D to accurately capture the phenomenon of shear localisation during the computational process. With the utilisation of a 3D model, the capacity to detect and record shear stress concentration becomes more refined, resulting in outcomes that closely resemble the actual conditions of the slope (Lin et al. 2020).

Furthermore, Figures 2, 3, 4 and 5 show that the depths of critical slip surfaces and critical displacements exhibit consistency within regions of weak soil as determined through 2D FEM and 3D FEM analyses. This consistency is particularly evident within Layer 1 and extends into Layer 2. These specific layers are characterised by SPTN values below 15. When the weak soil layer is located within the intermediate layers, the critical slip surface extends to the weak soil layer, as Moni and Sazzad (2015) described. Layer 3 comprises soil with an SPTN value between 16 and 36, considered intermediate strength, and Layer 4 consists of high-strength soil with an SPTN value exceeding 50. Therefore, the critical failure surface and critical displacement extend until Layer 2.

Finally, through both numerical computational, the obtained values of FOS of the existing slope are consistently below 1.30, indicating the slope does not meet the minimum requirement for the stability of unreinforced slope according to PWD of Malaysia (PWD, 2010). Therefore, effective slope stabilisation measures are highly recommended to mitigate the risk of slope failure and ensure the long-term stability of the slope. Based on the slope stability analysis and the condition of the slope area, suitable slope stabilisation could be designed to avoid slope failure in future.

CONCLUSION

In finite element analysis, mesh coarseness significantly influences the calculated FOS in slope stability analysis using 2D FEM and 3D FEM in PLAXIS. The mesh divides the slope into interconnected elements, impacting accuracy. Findings show that 2D FEM tends to be more conservative with lower FOS values, but 3D FEM provides slightly higher values due to its assumptions. Finer mesh coarseness decreases FOS but increases the maximum displacement. Critical slip circle locations are consistent, but maximum displacement values differ, with 3D FEM showing higher maximum displacement than 2D FEM. Finer meshes capture smaller and more details features, but coarser meshes save computation time. However, a coarse mesh oversimplifies the slope geometry and behaviour, leading to less accurate FOS results. Thus, to achieve reliable and precise results, it is important to strike a balance between mesh coarseness and computational efficiency. Adaptive mesh refinement techniques can be employed to refine the mesh in critical areas where higher accuracy is needed while maintaining a coarser mesh in less critical regions. Therefore, by understanding the capabilities and limitations of 2D and 3D numerical analyses, engineers can make accurate decisions in slope stability design and reduce risk in geotechnical engineering projects.

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DECLARATION OF COMPETING INTEREST

None

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