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***Research paper***

# Comparison of 2D and 3D Stability Analyses for Natural Slope

**Erly Bahsan[1]*, Rifani Fakhriyyanti [2]**

[1]*Department of Civil Engineering, University of Indonesia*
**Corresponding Author E-mail: erlybahsan@eng.ui.ac.id*

**Abstract**

Slope stability analyses are performed mostly as a two-dimensional (2D) section under the assumption of plane strain conditions, without much consideration to the impact of three-dimensional (3D) shapes. For natural slopes that have the complexities of slope surfaces, 3D modeling may also be considered since it can represent the more realistic geometry of the slope. However, previous studies show that the factor of safety (FS) as a result of 3D analyses mostly overestimated the FS from 2D analyses. This may lead to a long discussion on whether the 3D analysis is still applicable for the natural slopes, and could it represent the same results as the 2D analysis. This study was conducted using the finite element method for calculating the 2D and 3D FS of Pasir Muncang natural slope in order to observe differences of FS resulted from both analyses. A comparison of the FS from the 2D and 3D analyses, and also verification of sensitivity on several factors that impact the 2D and 3D models have been performed. The results of this study has indicated that some factors such as soil parameters, contour interval, and mesh coarseness greatly affect the results of the 2D and 3D calculations. Having carefully selected the aforementioned factors as the inputs for calculations, the difference between the FS values of 3D and 2D analyses becomes smaller. The final result of FS for this case study from the 3D analysis was still higher than the one from the 2D analysis, with the ratio of FS from 3D to FS from 2D was 1.44. It can be inferred that the use of 3D analyses needs more accurate data selections compared to the 2D analyses.

***Keywords***: *Slope stability; finite element method; 2D; 3D; factor of safety*

## 1. Introduction

The purpose of slope stability analysis is to estimate the safety of a slope by calculating factor of safety (FS) of the slope. Various methods exist for slope stability analysis, one of them is the finite element method (FEM). In FEM slope stability analysis, there are also the options of two-dimensional (2D) and three-dimensional (3D) analyses. The 2D slope stability analysis is the most common methods nowadays due to its simplicity, and also because it has a more conservative value of FS than the 3D analysis (e.g., [1]). The 2D analysis is performed under the assumption of plane strain conditions, without much consideration of the three-dimensional shape of the slope. Hence, 2D modeling often cannot represent the actual geometry conditions of the slopes, especially for natural slopes that have a complex geometry. Another advantage of 3D analysis is that the finite element procedure can show the least stable slope surface. This is not a case in the 2D analysis where the most critical section should be assumed in advance. However, it is expected that either the 2D or 3D analyses can provide a similar calculation results regarding the prediction of slope failure and the FS value. Therefore, this study has been conducted to compare the results of natural slope stability modeling in 2D and 3D by taking a case study of Pasir Muncang natural slopes, West Java, Indonesia. In addition, some factors that affect the slope stability analyses results were also investigated. The stability analyses and slope modeling in this study used the finite element softwares PLAXIS 2D and PLAXIS 3D.

## 2. Study Area

The case study that has been used here was the natural slopes tha located in Pasir Muncang Village, near Sindangkerta, about 25 km to the west of Bandung City, West Java, Indonesia, as shown by the dotted reactangle in Figure 1. The typical soil in that location is residual soil which usually identified locally as tropical red clay (e.g., [2]). A soil investigation had been conducted prior to this study by the Soil Mechanics Laboratory of University of Indonesia in July 2016 to obtain the subsurface information.

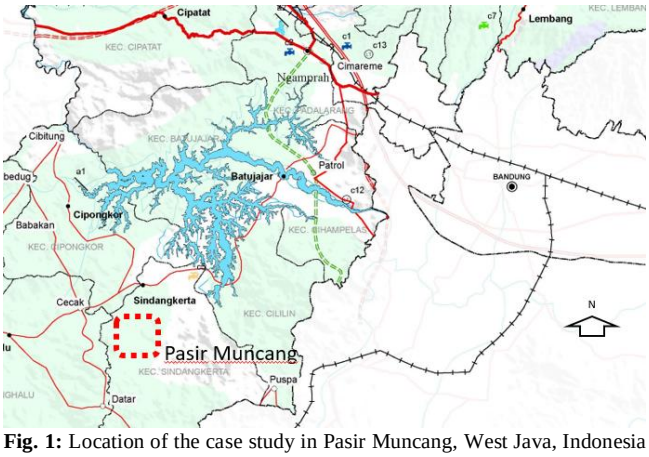



**Fig. 1:** Location of the case study in Pasir Muncang, West Java, Indonesia (reproduced from Ministry of Public Works, 2014)

Based on the results of field investigation and laboratory tests, it was assumed that the subsurface condition has three main layers

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(from the top to the bottom, respectively: (1) soft silty-clay layer, (2) medium sandy-silt layer, and (3) medium to hard sand layer). The thickness of the first layer was about 4 m, the second layer was about 10 m thick, and the third layer was not identified.

## 3. Literature Review

Previous studies had been done regarding the comparison of the FS as a result of 2D and 3D slope stability analysis. In [3] and [4] it is stated that the FS from 3D analysis always higher than the one from 2D analysis. A similar conclusion also infers by [5] after collecting some 2D and 3D slope stability calculation results. Another study by [6] comparing the results of various 2D slope stability calculations to a 3D stability calculation on different slope models: slope with a homogenous material, slope with a homogenous material and water table, and slope with different layered materials without water table. The results showed that the 3D calculation is slightly higher than most of the 2D calculations. The application of 3D and 2D slope stability calculation to a case in Southern California in [7] shows that the FS from 3D analysis is 1.6 times higher than the one from the 2D analysis. It is assumed that the shape of the slope in 3D analysis can influence the FS results. For example, the FS for concave slopes is higher about 5 to 20% than the straight (plane strain) slopes as mentioned by [8]. Another study by [9] also mentions that the concave slopes averagely has higher FS values. Considering all of those aforementioned studies, it is in a big interest to study how close the values of FS from 3D and 2D analyses can be, and what are the main factors that affect the calculation results.

## 4. Methodology

The methodology that was used in this study consists of several steps. First, literature review and secondary data collection. The required information was topographic maps and soil investigation reports. The topographic maps are very important regarding the shape of the slope surface that were used for 3D modeling as well as to get the 2D sections. The next step was to determine the soil layers and soil parameters based on the provided data. Those parameters then were used to build the slope models. The slope stability analyses in this study used the 2D and 3D finite element softwares (PLAXIS 2D and 3D). The FS as the results from both analyses then were compared, while some factors that may affect the calculation results were also observed. The first step in 2D slope stability analysis was determining the critical cross section that usually selected by observing the slope angles. The soil layers below the surface were drawn according to the assumption based on the soil data.

The soil layers' data for the 3D analysis were given by using some reference points on the surface that considered as the "bore-hole" points. Each point content the elevation, the thickness of each soil layer and all related soil parameters. The slope surface and the soil layers were then generated by the software based on the data that were given as input at those reference points. After the calculation, the software showed the deformation of the slope model that indicates the possible critical slope failure location. This critical failure location in the 3D analysis was then compared to the assumed critical cross sections in the 2D analysis, along with the FS values that were resulted from both analyses. The next step was to alter some factors that may impact the stability calculations such as ground water level, soil parameters, contour interval, and mesh coarseness. The FS results after those factors were corrected then being observed again.

### 4.1. Determination of 2D Critical Cross Section

To get the lowest FS from the 2D analysis, four cross sections were selected based on the topographic map of Pasir Muncang Village of West Java as shown in Figure 2. Section I was the cross section at the area that previously reported for a surface movement, which can be assumed to have an FS slightly higher than 1. Section II, Section III, and Section IV are selected regarding the steep slope surface according to the contour data. The slope angles for Section I, II, III, and IV are 17°, 19°, 30°, and 21°, respectively. The height of the slopes averagely between 10 to 20 m (see Figure 3).

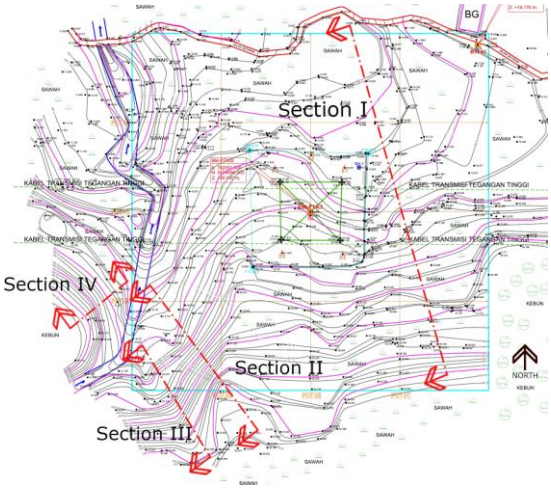
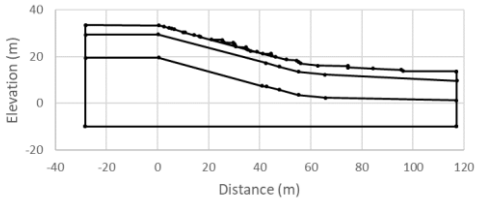
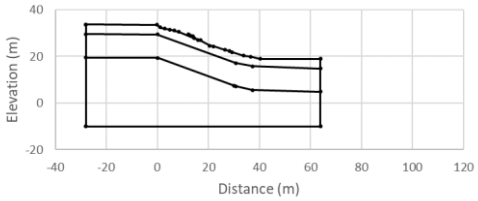



**Fig. 2:** Topographic map and the chosen 2D sections

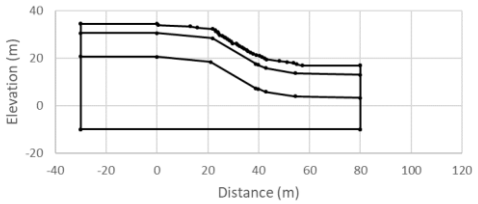
### 4.2. Geometry Modeling



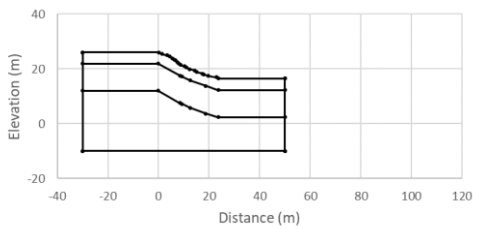

(a) Section I




(b) Section II




(c) Section III




(d) Section IV

**Fig. 3:** 2D sections for PLAXIS 2D

The geometry of slopes for each cross section (Section I to Section IV, respectively) in PLAXIS 2D was formed according to soil surface contour data as shown in Figure 3(a) to 3(d). Soil material used the Mohr-Coulomb model and drained material behavior.
The next step in the modeling was the mesh generation. Figure 4 shows the example after mesh generation for the 3D model, while Figure 5 shows the top view of the 3D mesh.

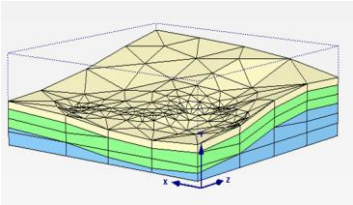


**Fig. 4:** The result of mesh generation on 3D model

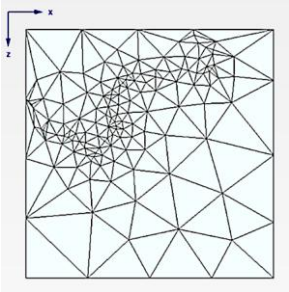


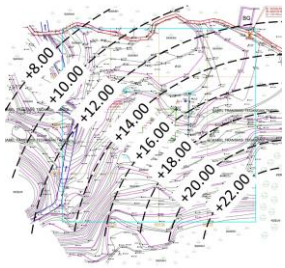
**Fig. 5:** Top view of the mesh for 3D model

The assumption for soil parameter that were assigned for each layers is shown in Table 1.

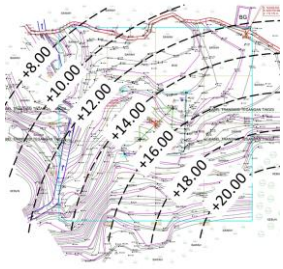
**Table 1:** FS from 2D calculations on different sections and

| Layer | $\gamma_{unsat}$ (kN/m$^3$) | $\gamma_{sat}$ (kN/m$^3$) | E (kN/m$^2$) | v | c (kN/m$^2$) | ϕ |
|---|---|---|---|---|---|---|
| 1 | 17 | 18 | 5000 | 0.35 | 15 | 15 |
| 2 | 18 | 19 | 7000 | 0.35 | 10 | 20 |
| 3 | 19 | 20 | 50000 | 0.25 | 5 | 30 |

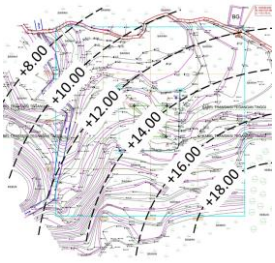
### 4.3. Ground Water Level




(a) GWL1




(b) GWL2




(c) GWL3

**Fig. 6:** The assumed contour of ground water level distribution

Three assumptions of ground water level distribution were used in this case study, as shown by the contour of water level in Figure 6. It was defined into three different conditions: GWL1 has the highest ground water level elevation at +22.00 m, GWL2 has the highest ground water level at +20.00 m, and GWL3 has the highest ground water level at +18.00 m. These ground water level condition were applied on both the 2D and 3D analyses. These ground water level assumption was made based on the water level depth data from 1 borehole, which showed that the water was found about 2 m below the surface at the time of the field investigation (rainy season).

## 5. Results and Discussion

### 5.1. Initial Result of 2D and 3D Stability Analyses on the Case Study

The results of the 2D natural slope stability analysis that were summarized in Table 2 show that Section III has the lowest FS for all the three ground water table conditions. These results were as predicted, since Section III has the steeper slope angle. Therefore, Section III as the most critical cross section in 2D analysis was then were compared to the results of the 3D analysis.

**Table 2:** FS from 2D calculations on different sections and different water level distributions

| Ground water Level | Section I | Section II | Section III | Section IV |
|---|---|---|---|---|
| GWL1 | 1,593 | 1,576 | 1,193 | 1,639 |
| GWL2 | 1,532 | 1,576 | 1,192 | 1,639 |
| GWL3 | 1,426 | 1,544 | 1,195 | 1,639 |

The comparison of the 2D cross section Section III with the 3D model that was summarized in Table 3 shows that there were differences between 2D and 3D FS as suggested by [7]. It states that the ratio of 3D to 2D FS is around 1.6. Slope model with ground water level condition GWL3 (the lowest ground water table) had the highest FS for 2D analysis, while in contrary the 3D analysis had the lowest FS. Theoretically, the higher water level should lead to lower FS due to the increase of mobilized forces. The anomaly in the 3D analysis regarding this ground water level effect possibly caused by the simplification of water table contour as shown in Figure 5. To get the more accurate results in 3D, it should require a more complex ground water contour.

**Table 3:** Comparison of FS from 2D and 3D analyses

| Ground water Level | FS 2D Section 3 | FS 3D | Ratio FS 3D/2D |
|---|---|---|---|
| GWL1 | 1.193 | 1.891 | 1.585 |
| GWL2 | 1.192 | 1.888 | 1.584 |
| GWL3 | 1.195 | 1.815 | 1.519 |

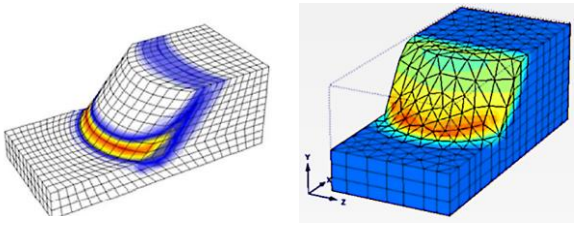
The factors that caused the difference in 2D and 3D FS are required to be identified. Verification of 2D and 3D behavior was done by re-built the same models that have been proposed by [10]. The purpose of this step is to check whether the procedure for building the slope model and the calculation procedure by the author was correct and can deliver reliable results. In addition, a remodeling of the cases in [11] and [9] were conducted to check the effect of geometry on the stability of 3D slope. Other tests that have been conducted includes the sensitivity tests on the change of soil parameters, contour interval, and global coarseness of the mesh in 2D and 3D analyses.

### 5.2. Validation of Behaviour of 2D and 3D Slope Stability Analyses

To ensure whether the modeling and calculation procedure in this study has been conducted properly, the author rebuilt the same models as shown in [6]. The result of re-modeling of [6] cases shows that the FS from re-modeling calculation relatively close to from the original (For the same 2D model, the FS from [6] was 1.70, while the FS from this study was 1.69. For the same 3D

model the FS was 1.80 from [6] and 1.81 from this study). This indicates that the calculations that were done by the author were relatively in line with the previous study. The presence of ground water levels and heterogeneity on the slope's layers have further decreased the FS in the 3D analysis. The FS from 3D and 2D analyses on a heterogenous slope (has more than 1 layer) have a larger difference than the FS from 3D and 2D analyses on a homogenous slope (has only one layer). Again, this was possibly caused by the simplification of the subsurface soil layer in the 3D analysis.

The influence of curvature on the surface of the slopes (concave and convex) in 3D slope stability analysis was studied through a re-modeling of cases in [10] and [9]. FS results of re-modeling the geometry in [10] were different from the original reference. The FS for concave slope in this study was 2.02, while the FS in [10] for the same case was 1.86. The FS for convex slope in this study was 1.87, while the FS in [10] for the same case was 1.76. This is possibly due to differences in methods and software used by [10] and authors for the 3D slope stability analysis (the previous studies used finite difference software for 3D analysis). Whilst the FSs were different, the re-modeling behavior was similar to the ones that have been done by the previous researchers. For example, Figure 7 shows the deformation results of convex slopes from this study and from [9], where both models have similar deformation pattern. The behavior of the results from re-modeled case of [10] also similar with the results from [12] and [13].



(a) (b)

**Fig. 7:** The deformations in 3D model from (a) [10] and (b) the re-built same model in this study

## 5.3. Effects of Contour Interval

The geometry of slope is a factor that has a significant influence on the slope stability analyses. The geometry of the Pasir Muncang natural slopes is highly dependent on the contour interval modeled in both 2D and 3D models. The closer the contour interval in the model, the geometry of the slope will be closer to the actual slope. However, the closer contour distance required bigger effort and time. A sensitivity test was done for the 2D and 3D models by observing the changes in slope geometry, FS, and slip surface, due to contour interval variation. The sensitivity test results for contour interval influences are summarized in Table 4.

**Table 4:** The effect of contour interval on 2D and 3D FS

| Analyses | FS | | |
|---|---|---|---|
| | 2 m | 4 m | 6 m |
| PLAXIS 2D | 1.245 | 1.426 | 1.698 |
| PLAXIS 3D | 1.815 | 2.028 | 1.986 |
| Ratio FS 3D/2D | 1.46 | 1.42 | 1.17 |

Based on Table 4 it can be seen that the wider contour interval has resulted in higher FS. The effect of contour interval is more significant in 2D models that can be seen from the greater change in FS compared to the change in 3D model results. The possible caused of this anomaly in 3D analyses may be caused by the generation of slope surface by the software that was interpreted from the inputs on some reference points instead of directly using the contour lines as provided by topographic maps.

## 5.4. Effects of the Selection of Soil Parameters

Another sensitivity test was to study the soil parameter influences in 2D and 3D analyses results. In this sensitivity test, the changes of FS in both the 2D and 3D analyses were observed after the modification on parameters of each soil layer. Sensitivity test of soil parameters used a control variable that was the 2D FS, an independent variable that was the soil parameters, and a dependent variable that was the 3D FS. This sensitivity test was done by changing the value of one of the soil parameters while the value of other soil parameters was not changed. The soil parameter was repeatedly changed until the 2D FS reach the point where it is nearly changed. The value of these parameters was then were applied to the 3D model and the change of the 3D FS was observed. The soil parameters that have been observed are cohesion (c), friction angle ($\phi$), unit weight ($\gamma$), Young's Modulus (E), and Poisson ratio ($\nu$). These are the most common parameters used in the Mohr-Coulomb FEM model. The soil parameters influence in 2D and 3D FS are summarized in Table 5; it is shown that the largest difference of the 3D FS before parameter alteration (FS 3D-1) and the 3D FS after parameter alteration (3D FS-2) occurred due to the alteration of shear strength parameters cohesion and friction angle (0.39% and 0.16%, respectively). It can be inferred that the 3D stability analysis is most sensitive to the selection of shear strength parameters.

**Table 5:** Changes of FS after alteration of soil parameters

| | Alteration of | | | | | |
|---|---|---|---|---|---|---|
| Model | $\gamma_{unsat}$ | $\gamma_{sat}$ | E | v' | c | $\phi$ |
| FS 2D | 1.245 | | | | | |
| FS 3D-1 | 1.815 | | | | | |
| FS 3D-2 | 1.813 | | 1.815 | 1.813 | 1.808 | 1.818 |
| % FS 3D | 0.11% | | 0% | 0.11% | 0.39% | 0.16% |

## 5.5. Effects of the Size of Mesh

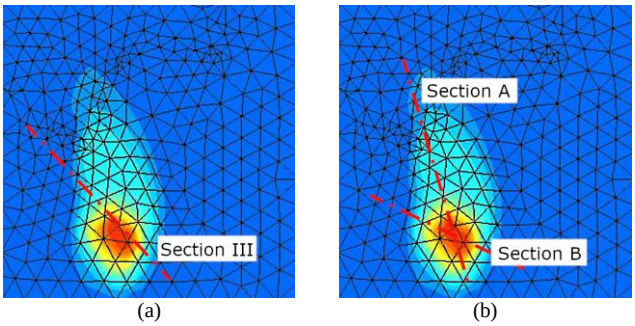
The last sensitivity test was to determine the effect of the global coarseness level of the mesh generation in the 2D and 3D analyses. This sensitivity test was modeled with five levels of global coarseness of mesh and under the condition of 2 meters contour interval. In PLAXIS, the coarseness of mesh is classified in 5 categories: very coarse, coarse, medium, fine, and very fine. The difference between each classs is the number of mesh in the model. The number of meshes in each category are around 50, 100, 250, 500, and 1000 for the very coarse, coarse, medium, fine, and very fine, respectively.

**Table 6:** The effect of global mesh coarseness on 2D and 3D FS

| Global Coarseness | Very Coarse | Coarse | Medium | Fine | Very Fine |
|---|---|---|---|---|---|
| FS 2D | 1.241 | 1.245 | 1.212 | 1.217 | 1.209 |
| FS 3D | 1.944 | 1.815 | 1.872 | 1.802 | 1.739 |
| Ratio FS 3D/2D | 1.57 | 1.46 | 1.54 | 1.48 | 1.44 |

Table 6 shows that the finer mesh tends to decrease the FS results. FS values from 3D analyses decreased up to 10.54% after the finest mesh size (ratio of the FS from the result using very fine mesh to the FS from the result using very coarse mesh), while in 2D models the FS decreased 2.58%. The interesting part to consider is that the mesh arrangement in the 3D analysis is affecting the generation of the 3D surface, hence it gives a significant influence on the FS. For a natural slope that has a curved slope surface, it is best to use the finest possible mesh size, since the finer mesh can generate the better curving geometry of natural slopes.

Using the finer mesh and the same contour interval, the locations of the critical slope failure from 2D and 3D analyses were being compared. Section III was chosen due to the similar location with the predicted failure location by 3D analyses.



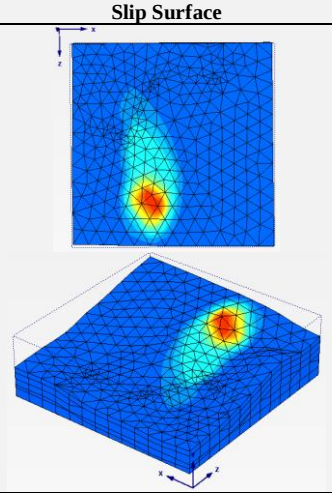
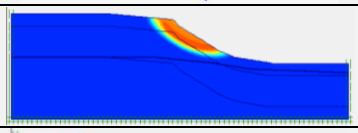
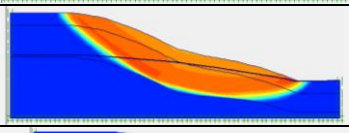
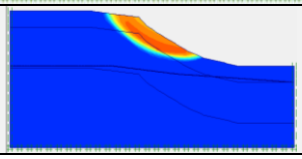

(a) (b)

**Fig. 8:** Comparison of the top view of the failure location in 3D analysis to (a) the Section III, and (b) new Section A and Section B

Based on Figure 8(a), it can be seen that Section III of the 2D model was located at the area of the most deformed surface in the 3D model. It shows that the most critical location of the 3D model was in line with the assumption for the critical cross section for the 2D model as assumed based on the slope angle. Furthermore, Section A and Section B as in Figure 8(b) was defined at the 3D critical location with different directions from the Section III. Comparison of 3D results and 2D analyses results for Section III, Section A, and Section B under GWL3 condition was summarized in Table 7.

Based on the results in Table 6, it can be seen that the 3D FS was 1.739 and the result of 2D analysis from Section III -- which has the lowest FS compared to Section A and Section B -- is 1.209. The difference ratio of 3D and 2D FS for this case was 1.44. This was the closest differences possible for this case after carefully correcting the aforementioned influencing factors. According to [7] the differences of 2D and 3D FS might be because the 2D analysis underestimates the side resistance of the slope, and it also neglects the shear resistance along the vertical surface of the potential slide mass.

**Table 7:** Comparison of 2D and 3D analyses results

| Analysis | Slip Surface | FS |
|---|---|---|
| 3D |  | 1.739 |
| 2D (Section III) |  | 1.209 |
| 2D (Section A) |  | 1.242 |
| 2D (Section B) |  | 1.268 |

## 6. Conclusion

Based on the results of this study, several things about the natural slope stability analyses for this case study with 2D and 3D finite element methods can be summarized as follows:

1. The factors that influence the result of slope stability analyses with PLAXIS 2D and PLAXIS 3D are:
   - The ground water surface modeling in 3D analysis required more effort related to the shape of the slope surface.
   - The difference of 2D and 3D FS are greater in heterogeneous slopes than homogeneous slopes.
   - In 3D analysis, slopes with concave shape have a greater FS than the slopes with convex shape.
   - The contour interval that was used for building the slope model also has an impact in FS. In this case study, 2D analysis with smaller interval resulted in lower FS, while in the 3D analysis this pattern was not showed due to the more complex geometry.
   - 3D slope stability analysis is more sensitive to the change of soil parameters compared to the 2D analysis. The most influential parameters to the change of 3D FS value are cohesion and friction angle.
   - In 3D modeling, the size of the mesh greatly affects the FS. FS in 3D analysis for this case study decreased up to 10.54% due to if using the finest mesh, while in 2D models the FS decreased 2.58% after the finest mesh. The finer mesh should bring a more accurate result.
2. The final result of FS for Pasir Muncang natural slope stability analyses were 1.209 from the 2D calculation and 1.739 from the 3D calculation. The ratio between 3D and 2D FS was 1.44.
3. In general, 3D modeling for natural slope stability analysis should be suitable for complex slope geometries and for the condition when there are difficulties to predict the critical cross section. However, due to the significant difference between FS from 2D and 3D analyses, it is necessary to adjust the target results of the analyses and to consider the availability of data in the selection of the 2D or 3D analyses:
   - The slope stability analysis that only concern on determining the FS should use the 2D analysis. The 2D FS is considered more conservative. Also, 2D modeling is easier than 3D.
   - The 3D analysis can be used if more detailed data are available such as the more accurate topographic maps, more accurate ground water conditions, complete information on the soil layers, with the detailed soil parameters. As for the example in this case study, it should use more borehole data from the field, so the rendering of the surface, the soil layers, and the ground water table could closely represent the subsurface condition in Pasir Muncang.

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