Column Resolution Impacts on 3D Open Pit Stability

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ABSTRACT
The 3D Limit Equilibrium Method (LEM) is a proven approach for increased rigor in aligning the modeling of open pit sidewall stability with reality but is subject to variation in the calculated factor of safety (FOS). Variations can be introduced related to the column resolution, the constitutive model parameters, and the critical slip surface searching methodology as well as additional aspects. This paper presents the analysis of column resolution influence and the related impact on the factor of safety (FOS) calculated on open pit sidewalls. This study provides insights on the critical surface shape, and evaluates how complex site conditions may also require column resolution refinement, to obtain a reasonable calculation time and accurate factor of safety. Methodologies are suggested for determining the optimum column resolution in practice.

RÉSUMÉ
La méthode d'équilibre limite 3D (LEM) est une approche éprouvée pour une plus grande rigueur dans l'alignement de la modélisation de la stabilité des parois latérales de la fosse à ciel ouvert avec la réalité, mais est sujette à des variations dans le facteur de sécurité calculé (FOS). Des variations peuvent être introduites liées à la résolution de la colonne, aux paramètres du modèle constitutif et à la méthodologie de recherche de surface de glissement critique ainsi que d'autres aspects. Cet article présente l'analyse de l'influence de la résolution des colonnes et l'impact connexe sur le facteur de sécurité (FOS) calculé sur les parois latérales de la mine à ciel ouvert. Cette étude fournit des informations sur la forme critique de la surface et évalue comment les conditions complexes du site peuvent également nécessiter un raffinement de la résolution des colonnes pour obtenir un temps de calcul raisonnable et un facteur de sécurité précis. Des méthodologies sont suggérées pour déterminer la résolution optimale de la colonne dans la pratique.

1 INTRODUCTION

Ensuring the stability of open pit sidewalls is central to the successful operation of open pits and the safe extraction of ore. Steeper sidewalls generally lead to more economic extraction of ore but results in additional risk in terms of stability. Historical slope stability analysis has typically involved 2D limit equilibrium methods (LEM).

When analyzing pits with complex geometry involving complex topology, groundwater conditions, and geology as anisotropic conditions, 2D methods can result in conservative designs. The potential advantage of being able to analyse and design open pit slopes using 3D Limit Equilibrium methods is therefore apparent from the safety, accuracy, mining optimisation and economic viewpoints (Fredlund et al. 2015).

Huang et al. (2002) when describing a generalized method for three-dimensional slope stability analysis observed the changes in factor of safety values versus number of columns for circular failures in cohesive slopes. The authors noticed f that when a sufficient number of soil columns were utilized, the calculated value of factor of safety was within an acceptable 0.7% difference with the close-form solution. The conclusion was made that the differences in the factor of safety result may occur from different ways of discretizing the failure mass in soil columns.

The common presence of geometry effects (concave or convex), and related anisotropic geo-strata effects on open pit factors of safety increase the need of understanding the real influence of column resolution in a 3D slope stability analysis. This is not only in terms of changes to the factor of safety, but also sliding mass volume, number of trial surfaces and consequently the total calculation time.

Previous studies have shown the comparison between the methods in 3D (Chaudhary et al., 2016) but few studies have been performed related to column resolution impact with stability analysis performed on complex structures.

1.1 Slope Stability Analysis in 3D

The advancement of 3D limit equilibrium methods (LEM) in software have resulted in a closer alignment to reality in geotechnical numerical modeling. The theory considered for solution has largely solidified around the use of the Spencer, Morgenstern-Price, or GLE (Fredlund) methods.

In a 2D analysis, any analyzed slip surface is divided up into a number of slices. Within the slope limits of a 3D LEM analysis (method of columns), the model is divided into number of rows (in Y direction) and number of columns (in X direction), composing the grid surface. The slope stability

3D analysis is carried out on the assembly of columns. Calculations of slope stability in 3D are based on the intersection points of the row and column lines (Figure 1). These points represent the column base center points. All parameters, such as material properties, water pressure, normal stress, and others are evaluated at the column base discretization.

Figure 2 illustrates the view of a failure mass discretized into columns and the main 3D forces acting on each column.

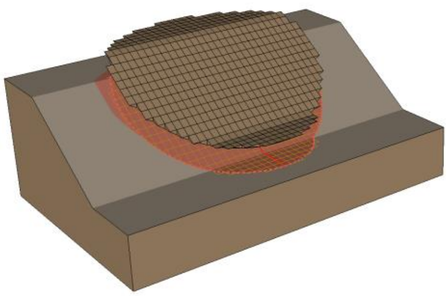

Figure 1. Failure Mass in 3D Limit Equilibrium Method composed by columns

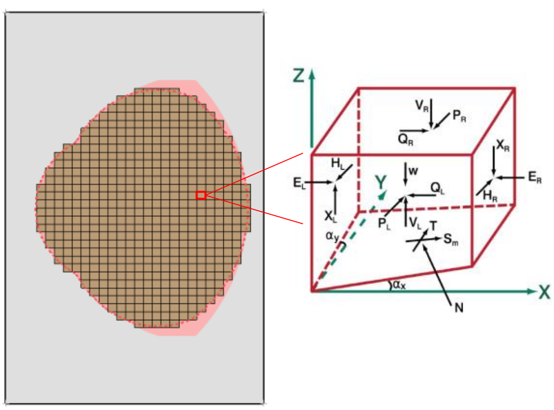

Figure 2. Column plan view and overview of acting forces in each grid element

2 METHODOLOGY

An open pit located in Australia utilized for iron ore extraction was modeled to apply the proposed methodology. The chose model presents complex geometry involving uneven benched topology and faults.

The analysis was carried out using the software PLAXIS LE 3D, developed by Bentley Systems, with the purpose of performing slope stability analysis through advanced search algorithms for soil and rock slopes. The chosen software includes the capability of adjusting grid resolution in details at convergence options, besides features such as oriented search planes and multiplane analysis that will be of important use during the applied methodology.

It's assumed that the surfaces topography is accurately represented by triangulated surface mesh objects.

The soil stratigraphy is composed by four different types of material, which in this case, are represented by the Mohr Coulomb constitutive model. The materials present peak strength conditions. A water table represented by a grid surface is also considered for the influence of pore-water pressures in the model. Figure 3 shows the 3D site representation of the model and the YZ plane view with inclusion of water table visualization.

The searching area will be located between concave and convex sidewalls of the pit, as presented in Figure 4. The initial step of methodology is focused on one critical region of the pit but could be easily replicated to other searching planes as based on engineering judgment. The multi-plane analysis (MPA) feature could also be applied to sweep the search spatially with globally selected column resolution settings.

As mentioned by Huang et al. 2002, two inherent sources of variability must be considered in 3D limit equilibrium analysis. The guessing of a plane of symmetry, and the assumed direction of sliding. For the present study, a multiple orientation slip direction was considered. Consequently, the critical search direction does necessarily follow the x-axis but can be at any orientation.

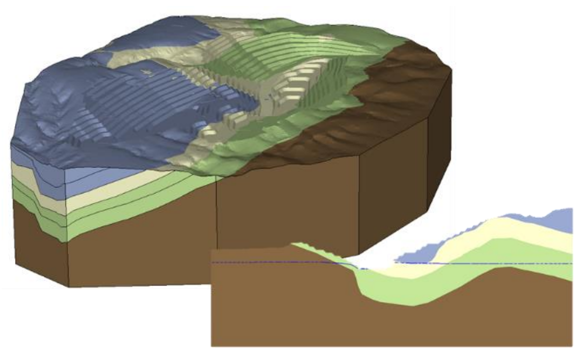

Figure 3. Open Pit model visualization

Figure 4 presents the oriented plane location and the selected direction angle of 248 degrees.

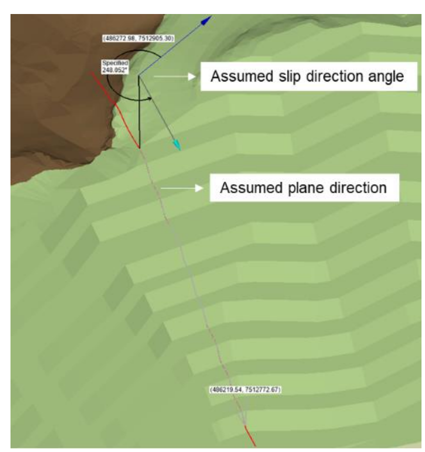

Figure 4. Plane direction location and angle

2.1 Scenario 01: Square Grid Resolution Analysis

To adjust the column resolution, it was required to create different scenarios regarding changes in the number of rows and slices under the model convergence settings. It is possible to vary rows and slices independently and 3D geometry effects may influence either in the direction of sliding or perpendicular to the sliding direction.

PLAXIS LE defines the rows/slices as extending across the entire model domain. The resulting width of each slice/row is reported when the number of rows/slices are defined. For comparing different resolution scenarios, a column ratio is used as reference point. The column ratio relates the row/slice width divided by the height dimension of each bench.

The bench height is constant and set as 10.0 meters in the present open pit example model.

The initial analysis considers only square grids, which means that the number of rows is equal to the number of slices (scaling factor equals to 1). The applied range was adjusted from 30 to 500 number of rows/slices across the entire model, consequently the column ratio varies from 6.6 to 0.4, which means that higher column resolution scenarios will lead to a lower column ratio.

In the practice of slope stability analysis in 2D, the number of slices generally vary from 30 to 50, this interval was considered in the 3D evaluation to demonstrate, especially in complex and large 3D geometry shapes, that the required minimum number of columns, in order to achieve a reasonable factor of safety, may increase to possibly three times the 2D resolution.

Figure 5 presents the grid resolution for the boundary scenarios considering a minimum column ratio of 6.6 and a maximum of 0.4. It`s visually intuitive that higher column resolution will also lead to a better alignment with the surface topography, which can be critical in cases like open pits, where the dimension of benches play an important aspect in the slope stability analysis.

The methodology considers only the changes regarding column convergence, the calculation method applied was GLE (Fredlund) and a local search method to truncate slope limits was used. Figure 5 illustrates also the red lines indicating entry and exit range of the searching plane.

Initial understanding of column resolution impact is shown in Figure 6 by plotting changes in factor of safety and calculation time regarding columns increasing when considering square grids. It's possible to notice that the factor of safety reaches a plateau in a certain stage of the analysis, representing that the slope stability analysis converged to a (almost) constant factor of safety, despite increases in column resolution and calculation time.

The factor of safety had to increase 68% until reaching the plateau. The calculation time kept increasing due to consequently increase in refining the failure mass number of columns

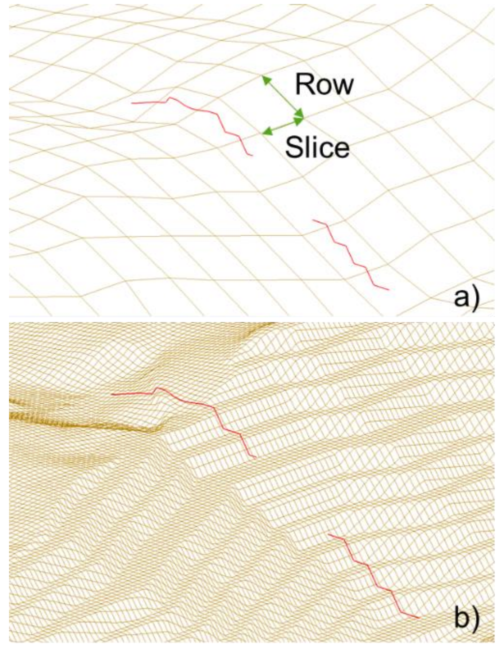

Figure 5. Grid Resolution with column ratio 6.6 (a) and 0.4 (b)

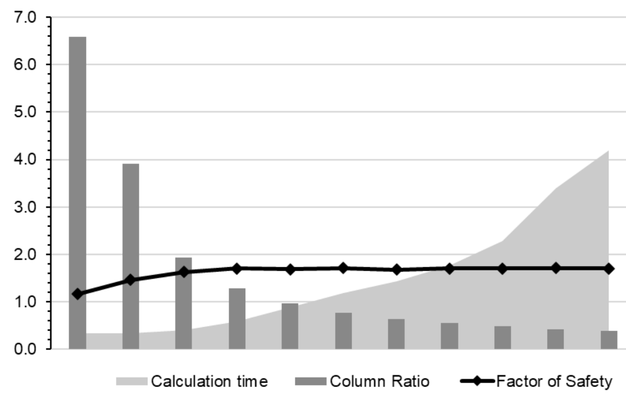

Figure 6. Factor of Safety versus Analysis Scenarios versus Calculation time

To define the reasonable initial column ratio required in the analysis, the volume mass was also plotted against factor of safety (Figure 7), demonstrating that the volume mass also reached a plateau, more specifically on Column ratio equals to 1.

As an initial conclusion, the rows/slice width equals to the bench height is a starting point for stabilizing factor of safety calculation.

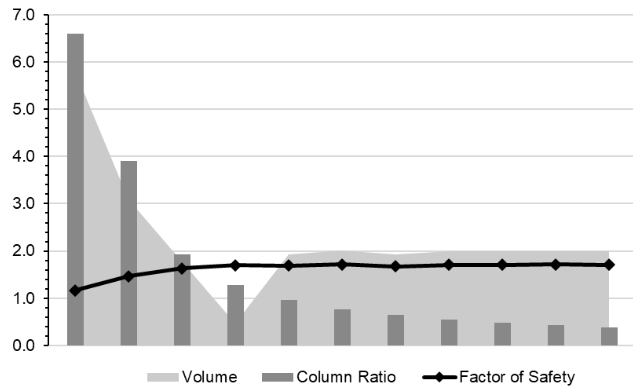

Figure 7. Factor of Safety versus Analysis Scenarios versus Failure Mass Volume

An important aspect of the methodology is visual checking of the critical sliding mass to provide further confidence on the appropriate column resolution. Figure 8 illustrates the failure mass for column ratio 1 and 0.4, respectively. The factor of safety mapped is less than 1.6% different, but in the failure mass center area, the surface depth is deeper, leading an additional material influence in the base column calculation, referring in the image as the brown area.

On the left side of the failure mass, the sliding corner limits are not well formed as the reference result of Figure 8 (b).

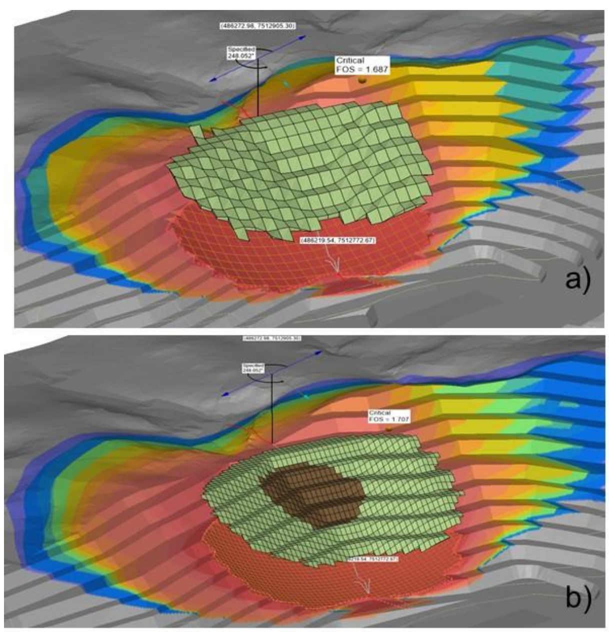

Figure 8. Failure Mass Visualization of Column Ratio 1 (a) and Column Ratio 0.4 (b)

Large open pit models require slope stability analysis around several regions along a 3D section/slope. Due to the geometric changes and anisotropic conditions, it's a common practice to verify the factor of safety under a 3D model in different plane locations. Considering this condition an important step of geotechnical modeling, it's also known that choosing to proceed with highest column resolution condition may significantly increase calculation time.

The visual comparison leads to the conclusion that column ratio 1 is similar in terms of factor of safety with a very refined case (Figure 8 b), but it still needs further investigation, or slightly refinement, to get the exact materials involved in the failure mass zone.

2.2 Scenario 02: Rectangular Grids Analysis

Spatial analysis using the multi-plane analysis (MPA) method requires a global setting of slice/row resolution. It is important to set the resolution globally such that any resulting small or large trial slip surface provides an accurate calculation of the factor of safety. Therefore, each trial slip surface of any size must have enough resolution such that the factor of safety calculation has reached the plateau for calculations described in the previous sections. It is therefore important for the user to select a minimum sliding volume and slip surface depth such that the smallest trial slip surface will calculate an accurate factor of safety in a reasonable time.

The second step in the methodology will consider additional modeling scenarios. The initial condition is a column ratio equal to 1, but now for rectangular grids, to understand if slight changes to the column ratio, more specifically on varying the slice spacing will provide accurate and reasonable results.

Rectangular grids are possible in PLAXIS LE by separately adjusting the number of rows and slices. This approach can be particularly useful for benches in open pits. As the previous generated grid will directly influence the method of columns calculation. It was therefore tested in the methodology if spaced grids (guided by changes in number of slices) respecting bench width (e.g., that the extension of the column is under the width), could affect the factor of safety.

This second step is guided by the understanding that lateral geometry is represented in the concavity. The intent is to confirm that there is a better representation of the lateral geometric sliding surfaces by increasing the number of slices when concave slip surface shapes are present.

Figure 9 illustrates an example considering (a) 200 rows and 200 slices (scaling factor 1:1) and (b) improved with 400 slices (scaling factor 2:1) In the second case the grid is better positioned along the bench width compared to the square grid.

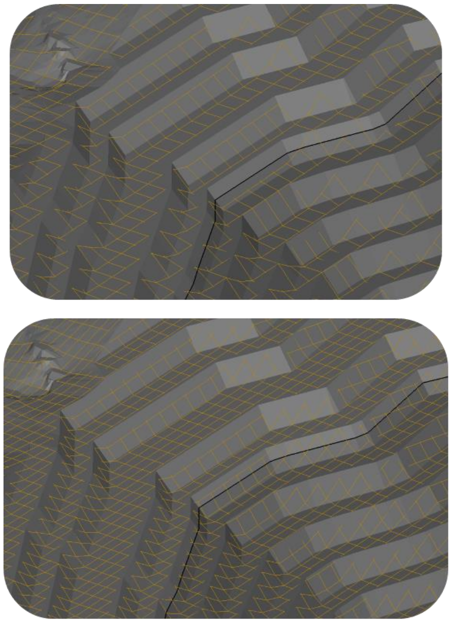

Figure 9. Grid resolution for a square grid (a) with 200 slices and (b) a rectangular grid with 400 slices

The scenario of column ratio 1 was adjusted into six additional models considering increments on the number of slices only, and six more increasing the number of rows only. The scaling factor in both cases varied from 1:1.05 to 1:2, which means that initial case was 5% and last case 100% higher.

The results obtained with the rectangular grids for slices variation demonstrated no considerable change compared to the reference factor of safety. Critical changes in calculation time were not also observed compared to column ratio 1 model, and the difference was about 17% higher. Also, the number of trial slip surfaces remained similar.

As scaling factor model of 5% increase in the number of slices was the one that obtained the same failure mass volume and factor of safety as model reference (column ratio 0.4), was then selected to be visually compared.

Compared to the observed failure mass in Figure 8, the model 200/210 (scaling factor 1:1.05) plotted in Figure 10 has a better geometrical distribution of columns along the sliding mass and also presented the inclusion of the same material influence as obtained for model reference in Figure 10 (b).

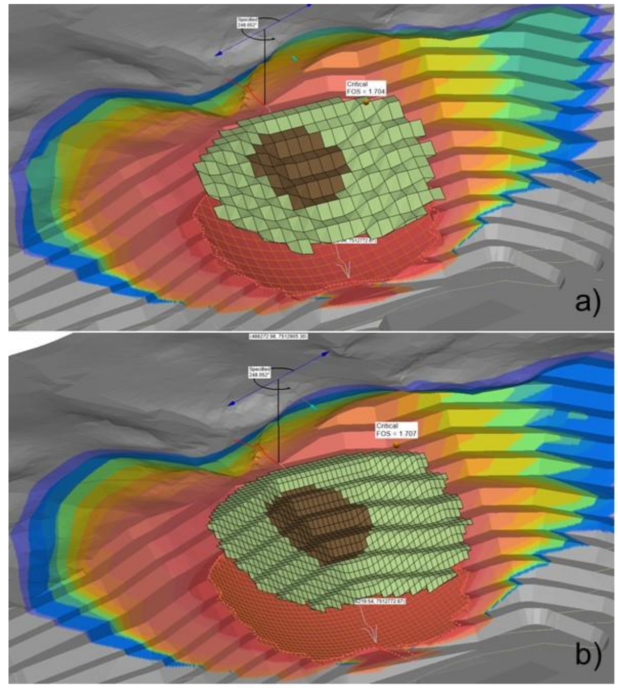

Figure 10. Failure mass visualization of (a) model 1:1.05 and (b) model reference

If the same slope stability analysis is done by varying only row spacing, the factor of safety does not present significant variation, similar results are observed for volume mass. But the sliding mass that achieves a comparable material zone influence as a reference model is only with a 25% increase, which means 200 slices and 250 rows. The scenario 1:1.05 did not reach a good visual comparable result, concluding that slice variation requires less resolution for reasonable results than row resolution for bench geometries.

It's important to mention that model 200/210 represents 25% of the calculation time of model reference and therefor is the chosen resolution for a reliable simulation in terms of slope stability results and model run-time for multi-plane analysis.

2.3 Scenario 03: Multi-plane Analysis

The chosen grid resolutions were considered for a larger verification area around of the whole pit. Using the multi plane analysis (MPA) concept, 31 searching planes were located respecting a 60-meter distance from each other. And similar settings regarding calculation and search method used as based on previous analyses.

One of the outputs provided with the multi-plane analyses (MPA) is the Factor of Safety contour map. The shadings translate an understanding of potential failure (or critical) slope stability regions, which would lead to a detailed analysis in specific open pit zones.

As based on Figure 11, the contour map plan view was visually compared for (a) model 200/210 and (b) model 500/500. Both results settings respected the minimum/maximum values and interval, and in that sense, it`s possible to understand by the shadings if the grid resolution would interfere critically on failure zones not potentially identified with a lower column resolution.

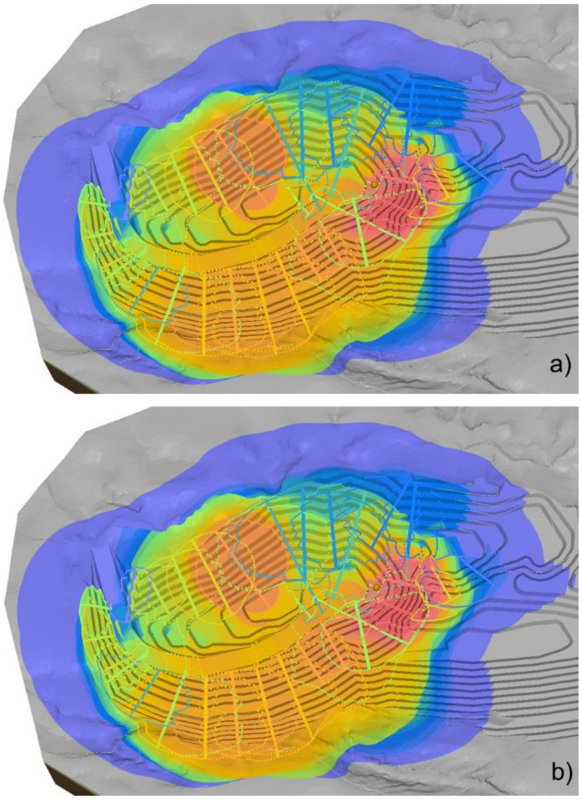

Figure 11. Factor of safety contour map – plan view: (a) model 200/210 and (b) model 500/500

3 CONCLUSIONS AND RECOMMENDATIONS

In theory additional columns will increase the accuracy of the factor of safety (FOS) but at the expense of additional computation time. Under a certain number of slices, the additional resolution will no longer result in changes in the FOS. The key to most analysis is to find the number of slices beyond which the FOS does not significantly improve, and the analysis could still finish in a reasonable time.

Based on the scenario evaluation, a column ratio less than or equal to 1 provides a reasonable calculation of the factor of safety for benches. It is recommended that model settings consider the condition of row/slice spacing less than or equal to bench height as starting point for reaching the factor of safety plateau.

The visual comparison is important and required between the scenario in which the factor of safety stabilized, and the one with 2.5 higher resolution (column ratio 0.4), for making sure that the same material base is being mobilized in both cases.

It was also observed that a lower increase of 5% in slice spacing presents better results compared to row spacing in benches, which took 4x higher increase in resolution to achieve comparable sliding mass.

The MPA analysis proved that the large evaluation of open pit sites can result in a similar FOS interpretation and critical spatial location when selecting an accurate column resolution.

For engineering practice, when handling 3D complex geometric models, selecting the most possible critical zone in terms of arching effects for local analysis is crucial. Different intervals of column resolution settings, based on engineering judgment, will lead to a factor of safety plateau, this graph portion has the potential to guide the ideal column resolution spacing for future modeling endeavors.

3.1 References

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