THREE-DIMENSIONAL (3D) LIMIT EQUILIBRIUM METHOD (LEM) COMPARATIVE STUDY OF A LANDSLIDE CASE STUDY SUPPORTED WITH PILES

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ABSTRACT

The Limit Equilibrium (LE) analysis of pile-supported geotechnical structures normally assumes a constant shear force for the pile instead of considering the non-linear capacity of the pile which is related to the pile displacement. In this study, a 3D Limit Equilibrium analysis is carried out for a landslide model supported with piles by considering the constant and non-linear capacity of the pile which is computed using a separate Finite Element (FE) algorithm. The depth of the pile, soil layering, and the pile properties are used with an assumed maximum displacement to compute the geotechnical non-linear capacity of the pile. In this study, the results of the initial unreinforced 3D LE model was first compared to the 3D FE analysis results. Then, the pile pattern was applied to the failure region in the 3D LE model, and then the factor of safety was recomputed. The results of the constant shear piles were compared to the model with the non-linear piles.

Keywords: slope stability, limit equilibrium, piles, finite element, 3D

INTRODUCTION

The accuracy of slope stability analysis has been a fundamental study in the geotechnical field for several decades. Providing preventative measures against slope failure due to stresses caused by gravity through soil has become a priority to minimize casualties and economical loss from damages to infrastructure.

Significant research has been accomplished in the field of slope stability analysis. The limit equilibrium method (LEM) and finite element method (FEM) are among the most popular approaches adopted by researchers and engineers. LEM provides simpler and faster analysis when compared to FEM. On the other hand, FEM has been known to be computationally expensive when the model is large in scale with finer mesh (Duncan 1996; Nian et al. 2008).

One of the most widely used methods for improving slope stability is via the reinforcement of slopes with piles (Zhang and Wang 2017). For pile-reinforced slopes, the complexity of analysis is increased due to soil-pile interactions. Some simple options for analysis include charts or closed-form solutions, limit equilibrium analysis, and continuum methods which use elastic piles (Carter et al. 2000). FEM can be used to replicate the interaction of nonlinear piles with soil constitutive behavior at the cost of computation time (Nian et al 2008). Recently, there has been increasing interest in soil-pile interaction analysis. One study has investigated the use of hyperbolic *p-y* models to capture nonlinear soil reaction and its effects on soil displacement and relative pile rigidity (Lei et al. 2021).

In this paper, a new approach has been introduced where the nonlinear capacity of the pile is applied into a limit equilibrium analysis. This coupled analysis method utilizes FEM for pile analysis with its nonlinear capacity strength criterion, which is then incorporated into LEM analysis for slope stability analysis. A slope without piles is first analyzed with LEM and verified with a FEM model. Then, the reaction forces supplied by the nonlinear capacity piles are incorporated into the LEM analysis to compare the results. The results were also compared with the results of the constant shear piles.

MODEL DESCRIPTION

The overall analysis approach taken in this paper is outlined as follows:

1. Determine the factor of safety (FS) for an existing slope without piles via LEM analysis using the Slide3 software.
2. The unreinforced slope analysis with LEM analysis is compared with FEM software, RS3.
3. The piles are analyzed with RSPile software to determine the allowable displacement that will produce the nominal drilled shaft structural mobilization.
4. The LEM is analyzed with nonlinear capacity piles analyzed from RSPile.
5. The results of the LEM model with non-linear piles were compared with the results of the same model with constant shear piles.

Soil profile

The existing soil layers and its material properties used for the LEM model is shown in Table 1.

Table 1. Existing soil properties for the model.

Material Name	Unit weight (lbs/ft^3)	Strength Type	Cohesion (psf)	Phi (deg)
API Sand	125	Mohr-Coulomb	0	35
Soft Clay	112	Mohr-Coulomb	0	15
Sand	142	Mohr-Coulomb	0	40

For the LEM analysis assumptions, the Janbu and Spencer methods were adopted. The full model contains material boundaries interpolated from multiple boreholes shown in Fig 1.

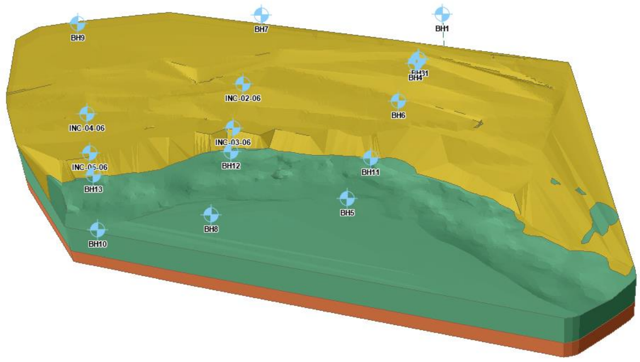


Fig 1. The geometry of LEM model.

Nonlinear Capacity Piles

The pile analysis is carried out with soil parameters outlined in Table 2. The piles are 8 ft in diameter and are socketed 16 ft into Sand layer. The assumed concrete strength is 5,000 psi. Transverse reinforcement is supplied via No. 7 GR60 hoops spaced at 6 in vertically on-center and with 6 in clear cover from edge of shaft to edge of bar. Longitudinal reinforcement is supplied via 27 No. 18 GR 60 bars (with reinforcement ratio, ρ =1.49%). The piles are spaced 40 ft apart along the section in and 24 ft in the out-of-plane direction.

Table 2. Soil parameters for pile analysis.

Model	Unit weight (lbs/ft^3)	Friction angle (deg)	Initial Modulus of Subgrade Reacion	Strain Factor	Undrained Shear Strength
API Sand	125	34	140 pci	-	-
Soft Clay	112	-	-	0.01	Consistent with Table 1
Sand (Reese)	112	15	10 pci	-	-
Sand	142	40	200 pci	-	-

The interaction diagram in Fig. 2 was adopted to estimate the constant shear and bending moment capacities of the pile section.

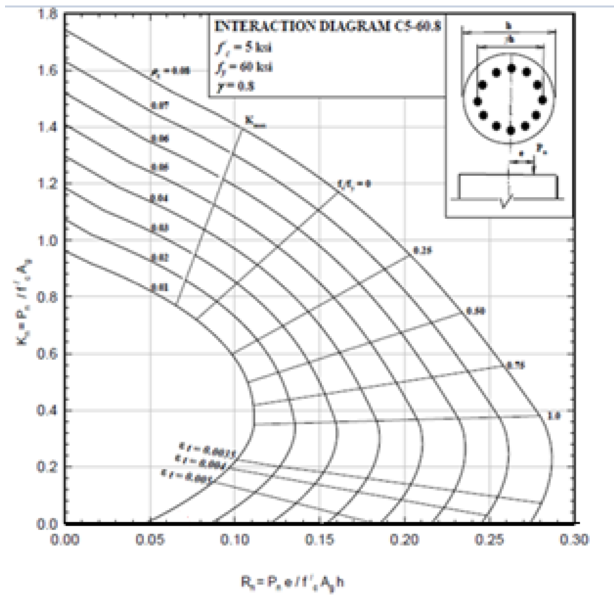


Fig. 2 Interaction diagram for circular columns, ACI SP-017 (2017).

ANALYSIS RESULTS AND DISCUSSION

Unreinforced Slope Model

The following section provides analysis results obtained from the unsupported slope in Fig. 2 using LEM. The analysis identified a critical slip surface with Spencer FS = 1.17 as shown in the left of Fig. 3. Sections A and B were created within the 3D model to analyze 2D analysis results, as shown in the right of Fig. 5. Note that the FS in 2D is generally lower than the 3D FS (Stark and Ruffing 2017).

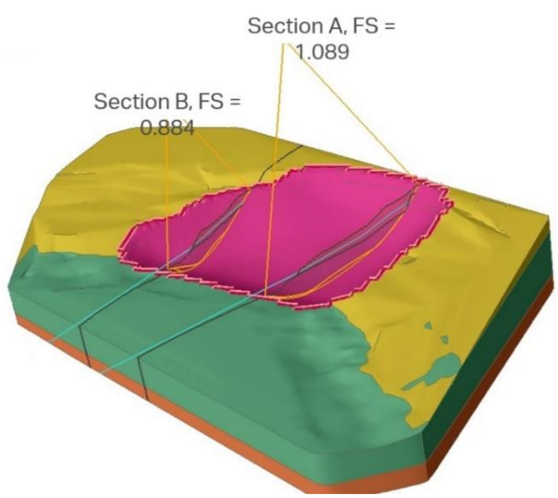


Fig. 3 Critical 3D failure region with Spencer FS = 1.17, and section A and B lower FS.

The LEM analysis is compared with unreinforced FEM analysis. The mesh and restraints for the FEM models are shown in Fig. *4*.

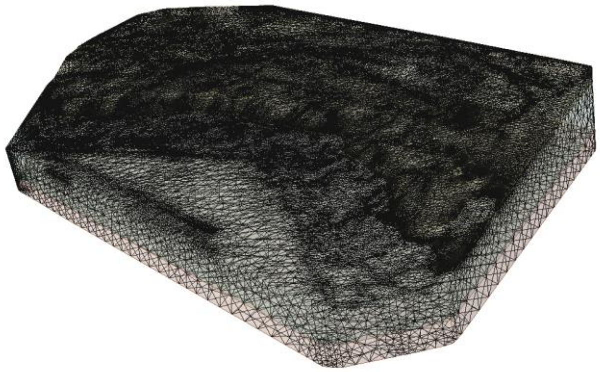


Fig. 4 FEM model with fine mesh.

The FEM analysis result shows a Strength Reduction Factor (SRF) of 1.16, which is in good agreement with the factor of safety of 1.17 obtained from LEM analysis.

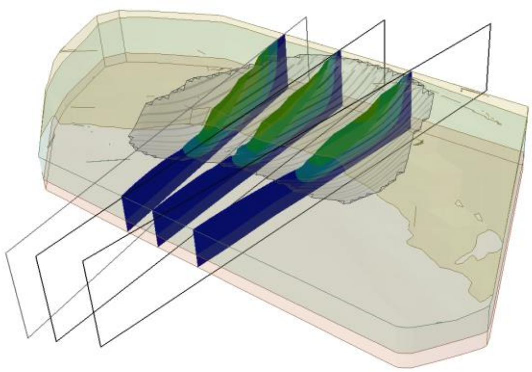


Fig. 5 Total displacement contours compared to surface result from LEM.

The grey surface on the model is the slip surface obtained from LEM analysis which is placed on the model for comparison. The sections on the model show the relative total displacements obtained from FEM, with lime-green representing to the highest displacements, and dark blue representing negligible displacements.

Nonlinear Capacity Pile Analysis

The piles were analyzed using RSPile software which utilizes the FEM capabilities built within software to analyze the nonlinear capacity of piles.

RSPile has been used to generate a lateral resistance envelope corresponding to 1.0 in of lateral soil displacement along the entire pile as shown in Fig. 6.

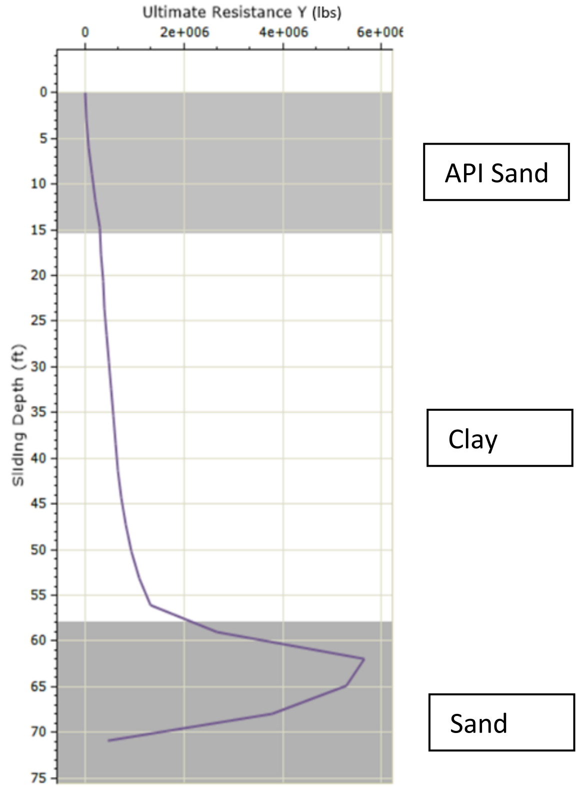
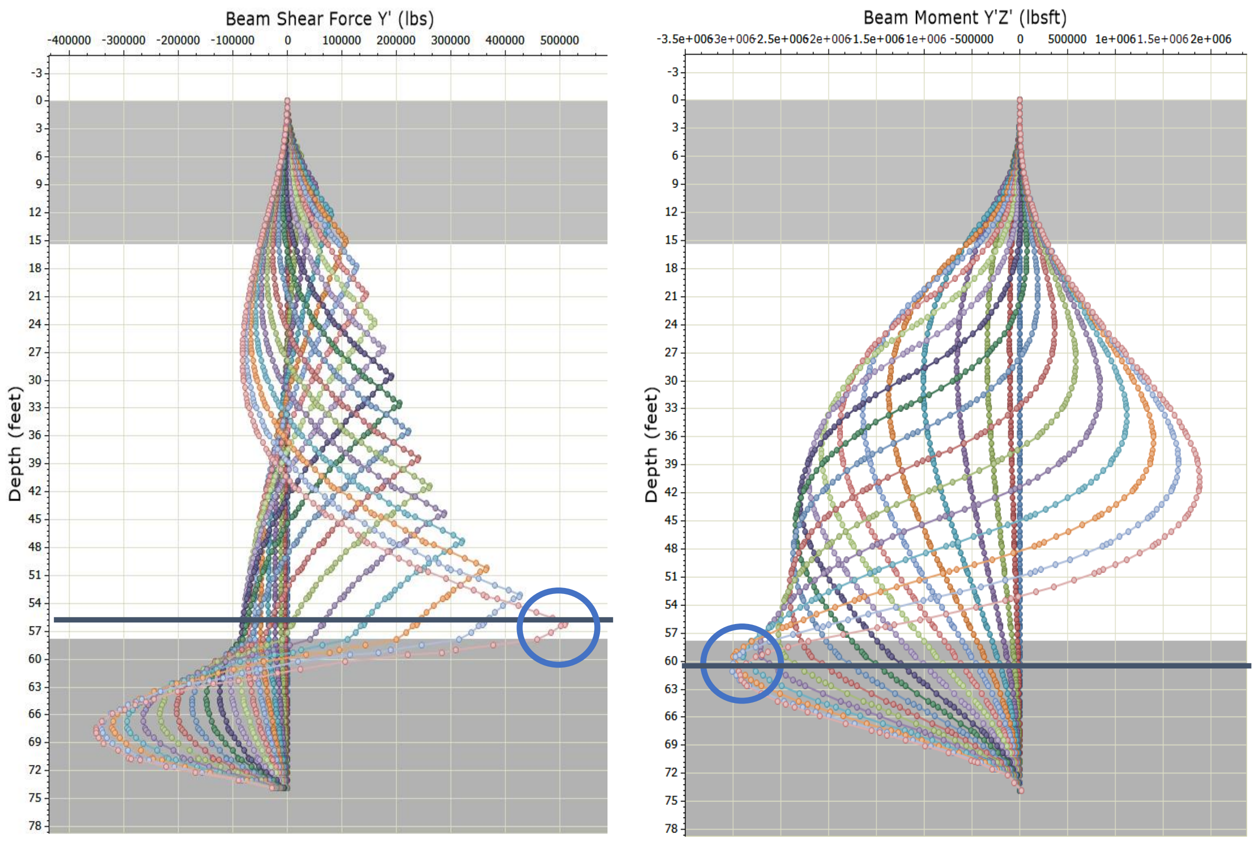


Fig. 6 Lateral resistance envelope corresponding to 1.0 in of lateral soil displacement.

In addition to the case of applying the 1.0 in displacement along the entire pile, the displacement of 1.0 in was also considered to be applied from the top of the pile down to various depths in order to create an envelope of shear force and bending moment diagrams shown in Fig. 7. Note that structural mobilization of piles corresponding with slip surfaces intersecting the piles in the Material 3 were excluded from the pile analysis, as the slope stability analyses indicated that critical surfaces will not penetrate the layer. 1 in is the maximum allowable displacement for the pile and the value of the shear will be picked depends on the depth of the failure surface in the LEM analysis.



Maximum Shear (V) occurs at 56' = 511 kips
Shear Capacity (V_n) = 1,964 kips
Max V/V_n = **0.26**

Maximum Moment (M) occurs at 61' when sliding depth at 53' = 3,014 k-ft
Moment Capacity (M_n) = 19,398 k-ft
Max M/M_n = **0.16**

***Fig. 7** Shear force and bending moment of pile at 1 inch displacement.*

The structural strength of the pile along its length up to a soil displacement of 4.5 inch can be reliable until it reaches maximum shear at a depth of 56 ft (right above the much stiffer Material 3). While it is unlikely that this amount of displacement would be experienced to provide support of such a deep sliding surface, it is a good exercise to determine the structural limits of the pile for a coupled analysis.

LEM Analysis with Nonlinear Capacity Pile Analysis

This section introduces the coupled analysis of LEM analysis with nonlinear piles. Figure 10 shows the input of the non-linear pile capacity into Slide3 as a user-defined support. The reaction of the pile was assumed to be equal to the value of the shear force diagram at the location of the slip surface with the pile. The shear force diagram was assumed to be the one shown in Fig. 8, with the pile being displaced 1.0 in along its entire length was inputted as the resistance of the pile. Since the original analysis in the RSPile software was developed for a 2D model, the reaction force from the support is perpendicular to the pile direction and then the resultant forces cause by the pile are calculated in the software in the XY plane. Thus, the axial demand due to the movement of the landslide in 3D is also ignored in this study.

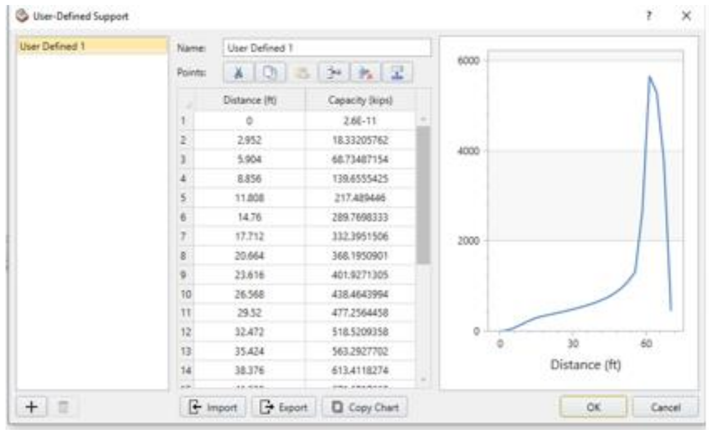


Fig. 8 User-defined support reactions obtained from RSPile analysis.

A screenshot of the model in Slide3 with the pile spacing dimensions are shown in Fig. 9.

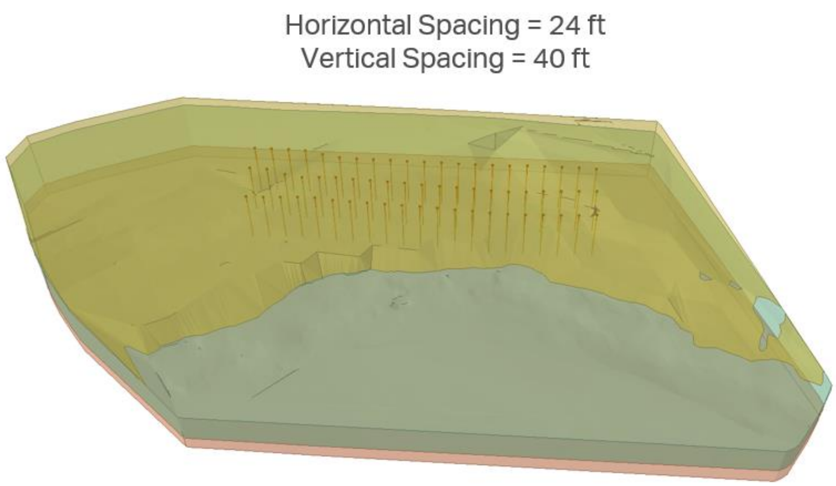


Fig. 9 LEM model with piles spacing dimensions.

With the support system defined by previous analysis, the LEM model with the nonlinear piles was analyzed to find the critical slip surface, which is shown in Fig. 10 with FS = 1.61.

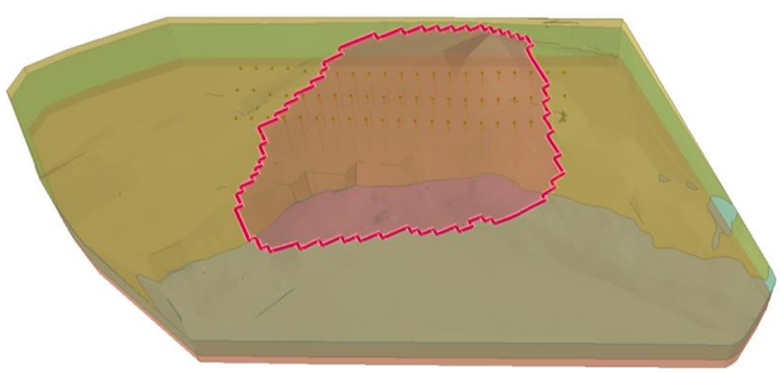


Fig. 10 LEM analysis result with FS = 1.61.

Compared to the analysis result shown without support (FS = 1.17), the supported slope with nonlinear piles shows significant improvement with a new FS of 1.61. Also note the change in the shape of the critical slip surface between the supported and unsupported LEM models, shown in Fig. 11.

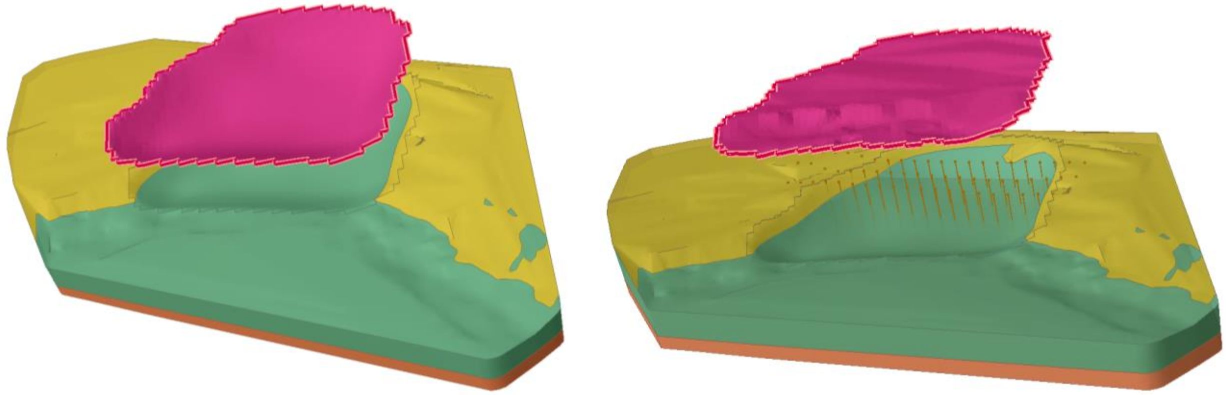


Fig. 11 Critical slip surfaces for unsupported (left) and supported (right) from LEM model.

The model was also analyzed with the constant shear pile for comparison. The average capacity calculated from the RSPile software was used, which was about 1,000 kips. Fig. 12 shows the failure surface with the Spencer FS = 1.98 for the case with the constant shear piles. With the average value of shear used for piles, the FS is significantly higher than with nonlinear piles. As such, using the average shear may be overly conservative for the design of piles. The reason for such high value is the fact that the point of intersection of the critical slip surface and the piles is different for different piles. Thus, for the non-liner piles, the intersection might be at the lower shear capacity than the average value which results in a lower FS for non-linear pile model compared to the constant shear model.

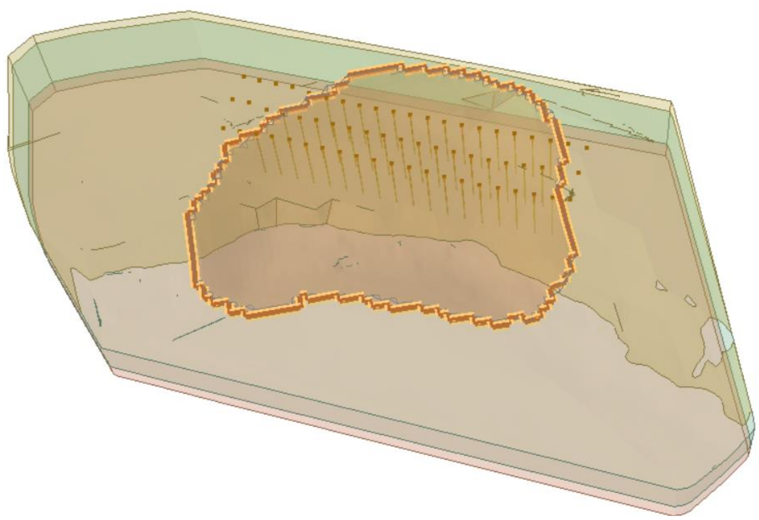


Fig. 12 LEM analysis with constant shear piles yielding FS = 1.98.

CONCLUSION

In order to minimize the potential hazard caused by slope failure, thorough investigation with analysis and design of supports is imperative to ensure safety of any infrastructure in the vicinity of the slope. Through the coupled numerical analysis of LEM and FEM models, the effect of reinforcing piles on the stability of an example slope was analyzed in this study.

The coupled analysis of nonlinear capacity piles is useful for considering the interactive behavior of piles and soils. The coupled analysis with nonlinear piles also showed lower factor of safety in LEM than with considering constant shear piles.

To further expand the applicability of this method, one suggestion in the future would be to incorporate nonlinear plasticity behavior of the piles subjected to seismic loads such as earthquakes or cyclic machine loads. This involves constitutive behavior of pile to soil interaction system which involves more complex integration method. This is out of scope for this study, but it would broaden the optimization of coupled analysis with 3D LEM model with nonlinear piles.

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