Two and Three Dimensional Limit Equilibrium Slope Stability Analyses: A Case Study in Oman

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ABSTRACT
Slope instability is one of the major problems in geotechnical engineering. Slope instability affects both man-made and natural slopes and may cause significant economic damage, and sometimes injuries and loss of lives. During the construction of the Musandam Independent Power Plant (MIPP) in Northern Oman, a rock slope failure occurred on a benched slope. This paper uses the noncircular two- and three-dimensional Limit Equilibrium Method (LEM) to determine factors of safety and probabilities of failure deterministically and probabilistically. Deterministic analyses are done using the General Limit Equilibrium Morgenstern-Price (GLE-MP) method combined with the metaheuristic Cuckoo search method and the Surface Altering local optimization technique. Probabilistic analyses are done using the stochastic response surface method which is more efficient than the traditional Monte Carlo simulation and Latin Hypercube simulation. The results of the analyses are compared to field data including post-failure geotechnical surveys and drone images of the failure surface. They are also compared to finite element analyses performed in a previous study.

RÉSUMÉ
L'instabilité des pentes est l'un des problèmes majeurs de l'ingénierie géotechnique. L'instabilité des pentes affecte à la fois les pentes artificielles et naturelles et peut causer des dommages économiques importants, et même parfois des pertes de vie. Lors de la construction de la centrale électrique de Musandam (MIPP) dans le nord d'Oman, une rupture du talus rocheux s'est produite sur une pente étagée. Cet article utilise la méthode de l'équilibre limite non circulaire en deux et en trois dimensions (LEM) pour déterminer les facteurs de sécurité et les probabilités de défaillance de manière déterministe et probabiliste. Les analyses déterministes sont effectuées à l'aide de la méthode Morgenstern-Price (GLE-MP) combinée à la méthode de recherche métaheuristique Cuckoo et à la technique locale d'optimisation Surface Altering. Les analyses probabilistes sont effectuées à l'aide d'une méthode stochastique qui est plus efficace que la simulation Monte Carlo traditionnelle et la simulation Latin Hypercube. Les résultats des analyses sont comparés aux données de terrain, ainsi qu'aux levés géotechniques post-rupture et aux images prises par des drone de la surface de rupture. Elles sont également comparées à des analyses par éléments finis réalisées dans une étude précédente.

1 INTRODUCTION

Rock slope instability is a natural hazard that occurs in many civil and mining engineering projects. This type of failure may cause catastrophic damage such as life loss, adverse environmental impacts, and loss of revenue (Sousa et al., 2022). There are many uncertainties associated with rock mass properties and deterministic approaches to assess stability are inadequate (see Einstein and Sousa, 2012; Sousa et al, 2014; Ivanova et al., 2014; Sousa et al.,2022) to assess the stability of slopes in rock masses. Rock slope stability can be affected by the geology of the project namely heterogeneities. Also, the engineering properties of a rock mass come with lots of errors namely weathering, discontinuities, and joint sets (Zhang, 2017).

To design a slope, conventional numerical techniques such as Finite Element Method (FEM), Limit Equilibrium Method

(LEM), Finite Difference Method (FDM), and others can be used to determine Factor of Safety (FS). However, these approaches are only able to capture FS deterministically. In order to consider uncertainties, such as the ones associated with discontinuities and ground engineering properties, the mentioned methods should be incorporated with probability simulations (e.g., Monte Carlo, Latin Hyper Cube, Response Surface, etc.) which consider the coefficient of variation and probability distribution of the soil parameters. This way one can obtain a distribution of the Probability of Failure (PF), along with a mean FS in slope stability problems (Pan et al., 2017; Guo and Dias, 2020; Guo et al., 2020; Dastpak et al., 2021). Obtaining a PF is important since, for example, two different slopes with similar geotechnical properties and geometry may have the same FS with PF which means that one may be associated with a higher risk of failure than the other.

To study the stability of the slopes both, 2D and 3D LEM are suitable choices since they meet both accuracy and time efficiency (Javankhoshdel et al., 2022). Javankhoshdel and Bathurst (2014) used LEM coupled with Monte Carlo simulations to study the effect of soil strength variability on the PF. Cami et al. (2021) used the 3D LEM approach combined with the Response Surface method to obtain the PF of an open pit considering different variability. Both studies showed good results.

More recently, scholars considered variability of spatial properties of the soil and rock masses in their numerical models to obtain more accurate results in terms of PF using Random Limit Equilibrium Method (RLEM) (Rafiei Renani et al., 2019; Izadi et al., 2020; Javakhoshdel et al., 2021; Dastpak et al., 2021; others). Javankhoshdel et al. (2021) showed that using a non-circular slip surface provides more accurate results when it comes to the RLEM. This is because the slip surface tends to pass through the looser parts of the soil mass leading to a non-circular slip surface.

In Oman, a rock slope failure happened during the construction stages of the Musandam Independent Power Plant (MIPP). Sousa et al. (2022) performed probabilistic studies of the MEP rock slope failure using three different methods namely the generalized Point Estimate, the Monte Carlo, and Latin Hype Cube. However, in their studies the number of samples considered was low and different possible variabilities to render PF where not considered. The main aim of this study is to extend the work by Sousa et al. (2022) using advanced 2D and 3D probabilistic LEM analyses. To this aim, the General Limit Equilibrium Morgenstern-Price (GLE-MP) method combined with the metaheuristic Cuckoo search method and the Surface Altering local optimization technique is used to capture FS using Slide2 and Slide3. Furthermore, in order to perform probabilistic analyses, the conventional LEM is combined with Latin Hyper Cube simulations and Response Surface methods for different analyses type, i.e., simple probabilistic or RLEM analysis.

2 MUSANDAM INDEPENDENT POWER PLANT

The Musandam Independent Power Plant (MIPP) is located in the Musandam peninsula in northern Oman. The MIPP is a plant with a capacity of 120 MW. The area of the site of the project is estimated to be approximately 350 m in width and 1000 m in length and is located 40 km southwest of Khasab, Oman. Fig. 1 shows the location of the MIPP. During the project construction, about 2.5 million cube meters of earthwork were needed. In previous years before the MIPP construction project, the site used to be a quarry for rock extraction. Several discontinuities were obvious on the site. The existence of these visible discontinuities required that any design of the slopes and their stability analyses in required in the project related to the needed earthwork, be elaborately computed for different foreseeable adverse conditions.

Fig. 1 Musandam Independent Power Plant (MIPP) location, Musandam Peninsula, Sultanate of Oman

3 2D FEM AND LEM MODEL

According to Sousa et al. (2022), the slope geometry is as presented in Fig. 2. The material properties of the rock used in both LEM and FEM are presented in Table 1. Sousa et al. (2022) used the Geological Strength Index (GSI) chart to obtain the equivalent Mohr-Coulomb properties, as per Hoek (2007) theory.

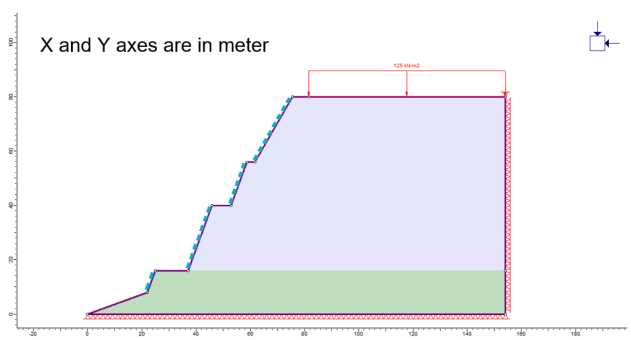


Fig. 2 Boundaries of the FEM and LEM model of MEP (Sousa et al., 2022)

The FS for FEM and LEM is calculated using Shear Reduction and GLE-MP, respectively. The FS was determined to be equal to 1.180, and 1.176 for FEM and LEM, respectively which shows a good agreement with the results obtained by Sousa et al. (2022). It should be noted that LEM uses a cuckoo search metaheuristic approach, a local optimization technique to find the failure surface, and surface altering optimization for the slip surface response and for the FS determination (Mafi et al. 2020). It can be seen in Fig. 3 that both FEM and LEM models yielded a similar slip surface.

Table 1 Material properties assigned in FEM and LEM (Sousa et al. (2022))

Material properties	
Friction angle (°)	40
Cohesion (kPa)	94
Unit weight (kN/m^3)	25
Yong modulus (MPa)	432
Poisson ratio	0.2
Earth pressure coefficient (K_0)	2.0

To investigate of considering the 3D effects on the modelling results, a 3D LEM model was developed. The 3D LEM was generated by extruding the corresponding 2D model by a distance of 310 m. All other parameters were kept equal to the values used in the 2D model. The FS obtained by the 3D model was equal to 1.22 which is a bit higher than that obtained by the 2D model. In 3D modeling, the differences between the 2D and 3D results depend mostly on the type of the geometry, material properties. In general, 3D extruded models with the same boundary conditions tend to have similar results to original2Dmodels. Fig. 4 shows the 3D model with the 2D factor of safety and its corresponding critical slip surface superimposed on. There is a good agreement between the 2D and 3D failure surfaces (2D failure surface is the orange line at the center of the 3D failure surface).

The 3D failure surface which was assumed to be elliptical was determined using the Cuckoo search method and the GLE-MP LEM analysis. As it can be seen in Fig. 4, the failure surface is similar to the real MIPP slope failure seen in the photo taken by a drone. The reason for developing the 3D model through extrusion of the 2D model is due to the lack of topographic data that is needed to develop a more accurate 3D model of the case study. Although this extrusion might cause some discrepancies between the failure surface results, the 3D model seems to simulate the failure scenario quite well.

4 PROBABILISTIC 2D AND 3D LEM

Two types of probabilistic analyses were performed: 1. Single random variable analyses (simple probabilistic analyses) considering Coefficient of Variations (COV) for soil strength parameters and 2. Spatial variability analyses based on the RLEM approach which considers correlation length of soil strength parameters in addition to the COV.

4.1 Single random variable analysis (simple probabilistic analysis)

Sousa et al. (2022) conducted a simple probabilistic analysis using Point Estimate, Monte Carlo, and Latin Hype Cube methods incorporated with FEM. The number of samples in their analysis was 100. The COV for friction angle and cohesion were 10%. In our paper, we extended their study by increasing the number of samples to 2000 (when using the response surface method) and to 15000 (when using the Latin Hyper Cube) samples for simple and spatial variability (RLEM) analyses, respectively. Three cases were assumed as per Table 2. The COVs considered were 10 %, 20 %, and 50 % for the friction angle and the cohesion. The PF captured based on these assumptions. It should be noted that the maximum values of 20 % for friction angle and 50 % for cohesion were chosen based on the work by Phoon and Kulhavy (1999). The probability distribution for all cases follows a gaussian distribution. For the simple probabilistic analyses, the method used was the overall slope where a different slip surface was found for every sample.

Table 2 COV assumptions for three different cases

	COV_φ (%)	COV_c (%)
Case I	10	10
Case II	20	20
Case III	20	50

The PF of 2D Case I, Case II, and Case III were equal to 5.6 %, 21.75 %, and 25.85 %, respectively. For the 3D modelling the PF obtained in Case I, Case II and Case III decrease to 1.95 %, 10 %, and 23.83 % respectively.

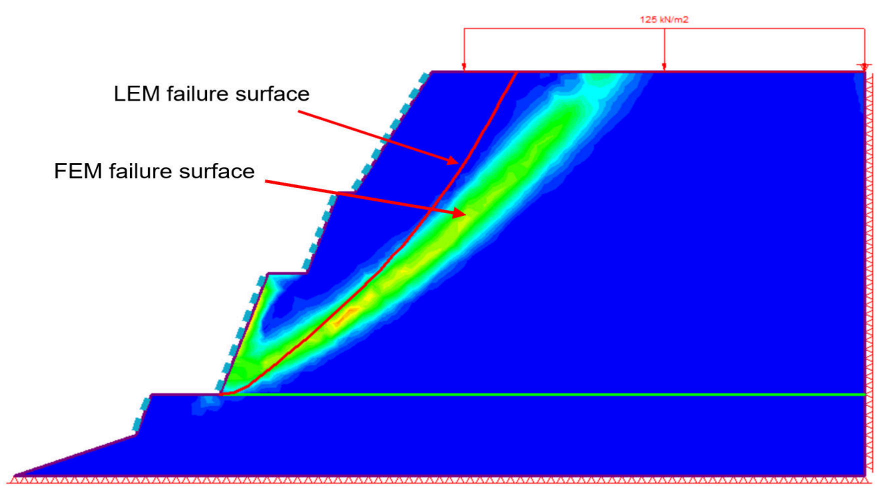


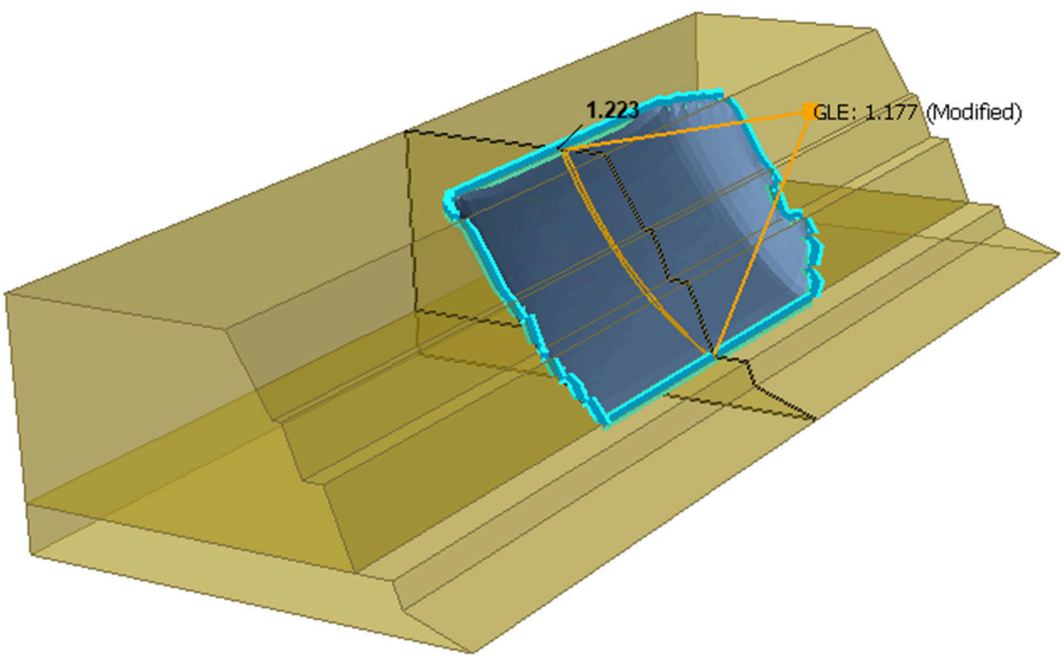
Fig. 3 2D slope failure of MIPP: LEM FS = 1.176; FEM FS = 1.18

Table 3 summarizes the PF in the 2D and 3D scenarios. As stated previously, 2D modelling results in lower FS. Yet the PFs for 2D cases are higher than 3D cases. This is because the variation of the soil parameters impacts more significantly 3D models. Since 2D models are a cross section of a 3D models, and 3D model failure can predict the change in parameters better than 2D.

Table 3 Summary of 2D and 3D LEM analyses

	FS	Case I PF	Case II PF	Case III PF
2D LEM	1.18	5.6 %	21.75 %	25.85 %
3D LEM	1.22	1.95 %	10 %	23.86 %

(a)



(b)

Fig. 4 3D slope failure of MEP: (a) actual failure, (b) 3D LEM (FS = 1.22)

4.2 Random Limit Equilibrium Method (RLEM)

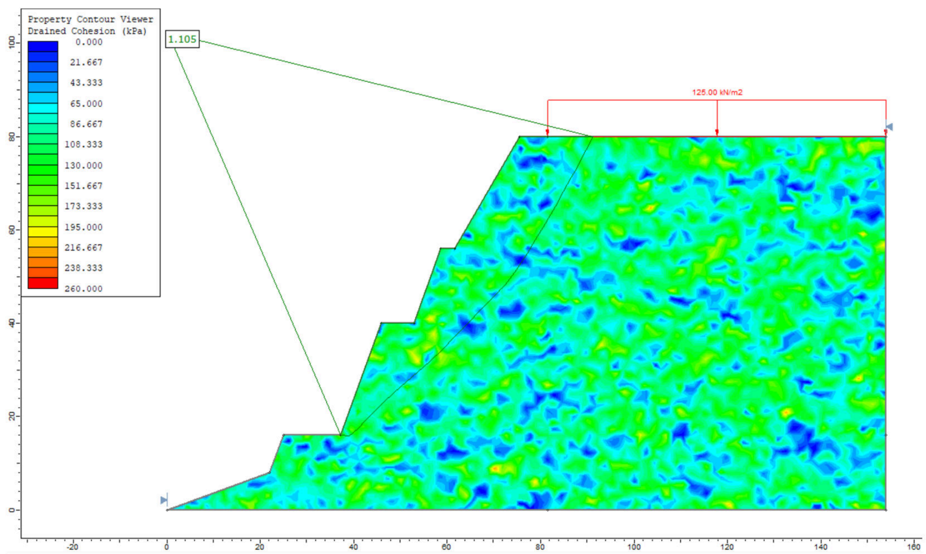
The spatial variable analyses, RLEM, were conducted with Slide2, which uses the local average subdivision method, introduced by Fenton and Vanmarcke (1990), to generate a random field. In this study, spatial correlation lengths for the strength parameters are assumed to be θ_V = 1 m for the vertical correlation length and the horizontal correlation length (θ_H) varied from 5 m to 40 m. These are typical values for the spatial correlation length for vertical and horizontal directions (Javankhoshdel et al., 2017). Fig. 5 shows the RLEM model for θ_V = 1 m and θ_H = 10 m. Based on the previous results obtained by Javankhoshdel et al. (2021) and many others, adding spatial variability to the soil parameters decreases the PF. Similarly, in this study, we observed that. The RLEM model approach yielded in very low PFs (near zero). Thus, the Reliability Index (RI) was used to examine the effect of θ_H on RI for different cases. The RI is calculated according to Eq. 1.

$$RI = \frac{\mu - 1}{\sigma} \quad (1)$$

Where μ is mean FS, σ is standard deviation of FS.

Fig. 6 shows the variation of Reliability Index (RI) versus horizontal correlation length for different cases. It can be observed that for a given case, the RI remains relatively constant with changing θ_H. However, RI decreases when COV increases. In fact, when COVs are lower, e.g., Case I, the slope is more reliable than COVs are higher. Fig. 6 also shows that the change in the COV of cohesion has greater effect on the probability of failure than the change of COV of the friction angle does.

Fig. 7 shows the FS histogram for 2D LEM, 3D LEM, and 2D RLEM with θ_H = 5 m for Case III. The results show that considering spatial variability of the rock mass properties narrows the FS histogram and probability of failure decreases (i.e., P(FS<1). Also, the 3D FS histogram becomes wider due to changes in COVs which is more significant in 3D models.



X and Y axes are in meter

Fig. 5 Example of noncircular slip surface in RLEM, Case III, θ_V = 1 m and θ_H = 10 m

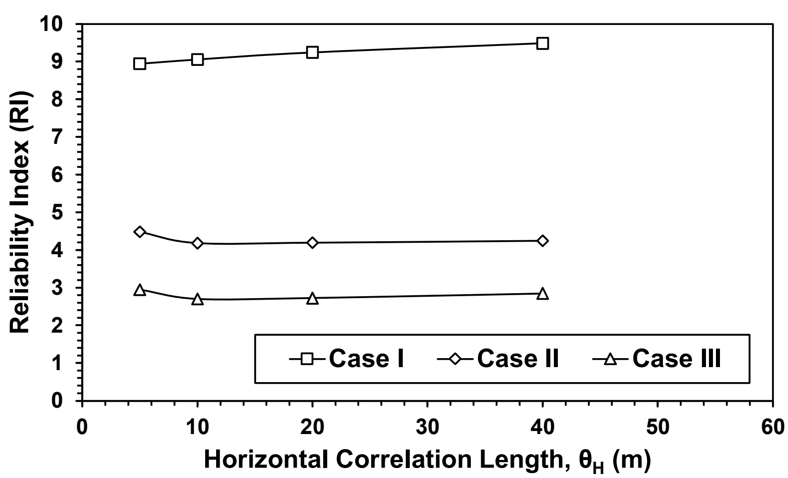
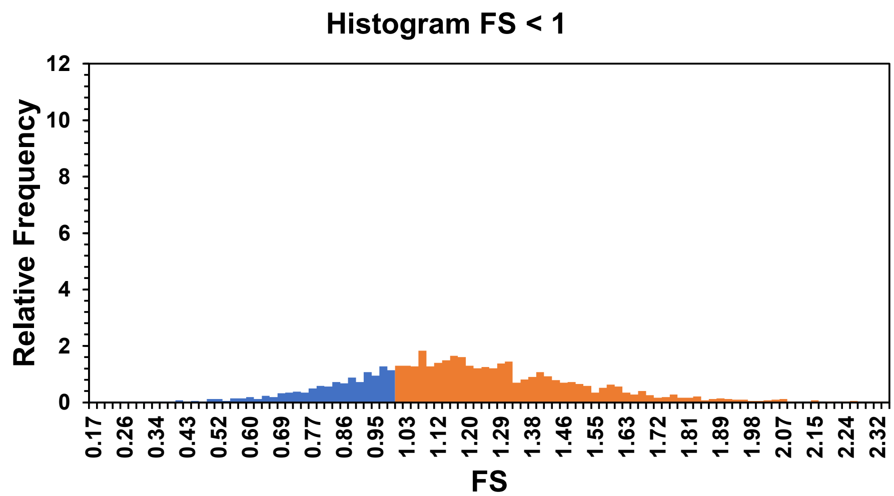
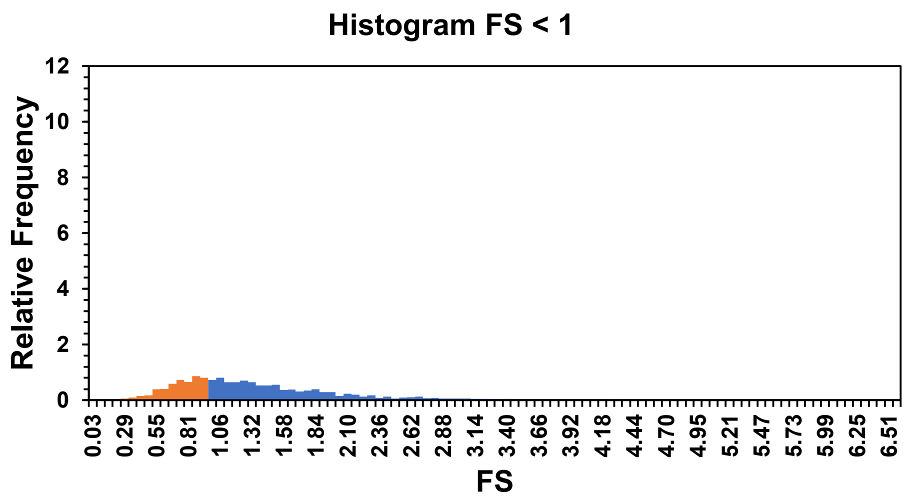


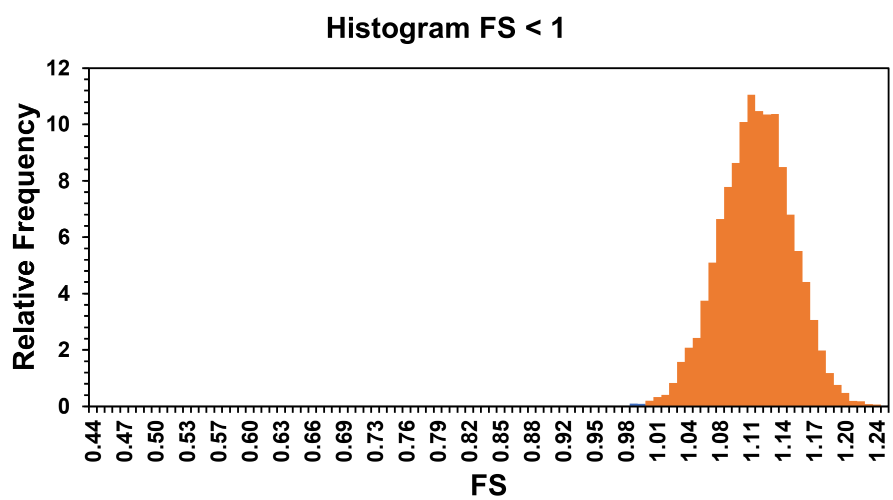
Fig. 6 Variation of Reliability Index (RI) versus horizontal correlation length for different cases



(a)



(b)



(c)

Fig. 7 Case III FS histogram; a) 2D LEM, b) 3D LEM, and c) 2D RLEM (θ_H = 5)

5 CONCLUSION

During the construction process of Musandam Independent Power Plant (MIPP), a rock slope failure happened. This study conducted a probabilistic study using both simple probabilistic analysis and Random Limit Equilibrium Method (RLEM) approaches in 2D and simple probabilistic analysis in 3D. The Mohr Coulomb equivalent soil strength parameters, i.e. friction angle and cohesion, were determined based on rock mass properties by using the Hoek (2007) Geological Strength Index (GSI) chart. Typical values of the spatial correlation length were assumed for the RLEM part of the study.

Three cases were assumed based on the coefficient of variation (COV) of strength parameters. The COVs were: $COV_c = COV_\varphi = 10\%$, and $COV_c = COV_\varphi = 20\%$ for both cohesion and friction angle (Case I and Case II) and for the Case III, $COV_c = 50\%$ and $COV_\varphi = 20\%$. In general, in this study, the FS is higher for 3D LEM in contrast with 2D LEM and the Probability of Failure (PF), for 2D cases are larger than 3D cases for all cases. This shows the influence of variability on 3D results which is more pronounced than in the 2D equivalent model.

The results obtained from 2D RLEM analyses, yielded very low PFs, in the order of 0.01% (high-reliability index), and the PF remains almost constant when the horizontal correlation length of strength parameters increases from 5 m up to 40 m for a constant vertical correlation length. The reason for lower value of PF in the RLEM case is that considering spatial variability of soil properties reduces the level of uncertainty in the probabilistic analysis. Further studies should be carried out to consider the cross-correlation between the soil parameters to even lower the current PF (increased RI) to match these numbers with the practical design values.

In general, this study showed that different assumptions of variabilities and probabilistic approaches can capture very high or very low PFs. Depending on the type of geology it is important to know if one should consider the spatial variability for a rock mass or not. In fact slopes in rock are many times govern by existing discontinuities and “homogenous” spatial correlation length like the one used in this study may not be the most appropriate, since the RI obtained was very high for all the cases of the RLEM analyses, but the actual slope failed.

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