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2D and 3D rock slope stability assessment using Limit Equilibrium Method incorporating photogrammetry technique

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Abstract: Advancements in technology have made it possible for acquisition and analysis of geological structure data in a short time, cheaper and safer than traditional method. Engineer sometimes failed to model the actual slope geometry due to the factor of accessibility and carry out those measurements at site. But with the aid of UAV photogrammetry technique, they can easily export the 3D model into any slope stability assessment software to perform the analysis. Photogrammetry is a technique used for rock slope assessment. Recent progression in modern UAV technologies such as photogrammetry technique using georeferenced UAV imagery allow us to obtain accurate surface profile including detailed slope information for the three-dimensional stability analysis. These techniques also mitigate the risks at site associated with conventional method. Large number of three dimensional coordinates in the form of dense cloud point can be extracted from only a few images. Dense cloud point imported to the Rocscience Slide version 2018 and Slide 3 version 2017 which is a 2D and 3D limit equilibrium slope stability software that evaluates the factor of safety (FoS) of circular or non-circular failure surfaces of soil or rock slopes. The rock slope parameters are obtained via laboratory test and rock database in Rocscience RocData were used in the assessment. Probabilistic method is performed to compute the 2D slope stability according to the normal distribution of the rock parameters on the global minimum slip surface. FoS of slope analysed by probabilistic method is 0.336 for least and 0.596 for mean FoS. Deterministic analysis is carried out to compute the 3D slope stability and the outcome are global minimum slip surface and the FoS of the entire rock slope. FoS of the rock slope without anisotropic plane is 1.960 and with anisotropic plane is 0.908. Thus, the use UAV to acquire 2D and 3D model of the rock slope is possible and stability analysis can be carried out to generate FoS of the slope as preliminary characterization.

Keywords: 2D slope stability, 3D slope stability, rock slope, limit equilibrium, photogrammetry

INTRODUCTION

Malaysia is a mountainous country where almost half of it is over 150 m above mean sea level and covered by granite, limestone, stratified rocks, igneous rocks, alluvium, etc. The nation's development involving building of infrastructure such as expressways through the mountains is unavoidable as for the improvement of the connectivity and accessibility between one city and another. Rock mass is a high strength material if it is homogeneous and isotropic. Nevertheless, rock mass is heterogeneous and anisotropic since it consists of discontinuities due to the stresses induced by movement of tectonic plates and weathering effect. A discontinuity will manifest most commonly in a rock mass as joints, faults, bedding surface, or blast impact. The orientations of the discontinuities contribute to the reduction in strength of the rock mass. Thus, it is vital to identify the discontinuity data in a rock slope.

There are many ways available to obtain the rock slope discontinuity information. Recently, the current advancement of new remote sensing strategies, such as Structure from Motion (SfM) photogrammetry and Terrestrial Laser Scanning (TLS) or LiDAR Scanning permit the obtaining of Earth surface information in a precise and fast way. SfM is a photogrammetric method for creating three-dimensional (3D) models of topography from multiple overlapping and stitching of two-dimensional (2D) photographs captured from multiple locations and orientations to reconstruct the photographed scene. In addition to ortho-rectified imagery, SfM produces a dense point cloud data set aligned with the coordinates obtained from Global Navigation Satellite System (GNSS) that is similar in many ways to that produced by TLS. Unlike high-resolution topographic surveying which is associated with high capital, SfM is an inexpensive, effective and flexible approach in capturing complex topography (Johnson *et al.*, 2014). It is cost effective and easy of use compared to TLS. Decimate-scale vertical accuracy can be achieved using SfM even for sites with complex topography and a range of land-covers (Westoby *et al.*, 2012).

Unmanned aerial vehicle (UAV) with camera mounted on it is used to obtain photogrammetric data. The photogrammetry approach is used widely in geomorphological environments and rock slope mapping for discontinuity characterization (Dall'Asta *et al.*, 2017;

Tannant, 2015; Turner *et al.,* 2015). UAV images can produce slope map of the real site study area with highly accurate results (Tahar, 2015). With the output from the photogrammetric processes, the rock outcrop can be seen clearly with its geological planes. The data extraction from the geological planes is very important as it is one of the main inputs for the rock slope stability analysis (Tung *et al.,* 2018). Limit Equilibrium Method (LEM) is the most common slope analysis method as it is a relatively simple and quick analysis. The data required for analysis can be easily collected from the field (Tang *et al.,* 2017).

There are two ways in analyzing the rock slope stability: deterministic method and probabilistic method. Deterministic method uses the exact parameters input for analysis and only one output can be obtained. However, the probabilistic methods facilitate to incorporate parameters, which show uncertainty, in a systematic way and define the stability condition of the slope in probabilistic terms. For probabilistic analysis of a slope having plane mode of failure, the parameters to be used are first defined as fixed dimension parameters and as random variables (Hoek, 2007). Fixed dimension parameters are mainly the geometric parameters which can be obtained directly from the geometry of the slope such as; slope height, slope inclination, upper slope inclination and dip of the potential failure plane. The random variables are those which show uncertainty in their values and may vary considerably such as; cohesion and angle of friction, ratio of depth of water in tension crack to the depth of the tension crack (Hoek, 2007).

FoS is the ratio between the resisting forces and the driving forces. Since some of the parameters used in resisting and driving forces are random variables, the parameters will have probability distribution over certain range, rather than a fixed absolute value. Thus, the probabilistic analysis will also provide FoS as random variables with probability distribution (Raghuvanshi, 2017). In Monte-Carlo Simulation Approach, from the probability distribution of each variable, discrete values are randomly selected. Later, FoS is evaluated by utilizing a set of different discrete values of various parameters. Multiple simulations are made by repeating the process by taking different set of the discrete values of various variables (Zhao *et al.,* 2016).

BACKGROUND OF STUDY AREA

The study area is located at the northern region of Peninsular Malaysia. It is the construction site of Projek Rancangan Lencongan Banjir Barat Timah Tasoh where

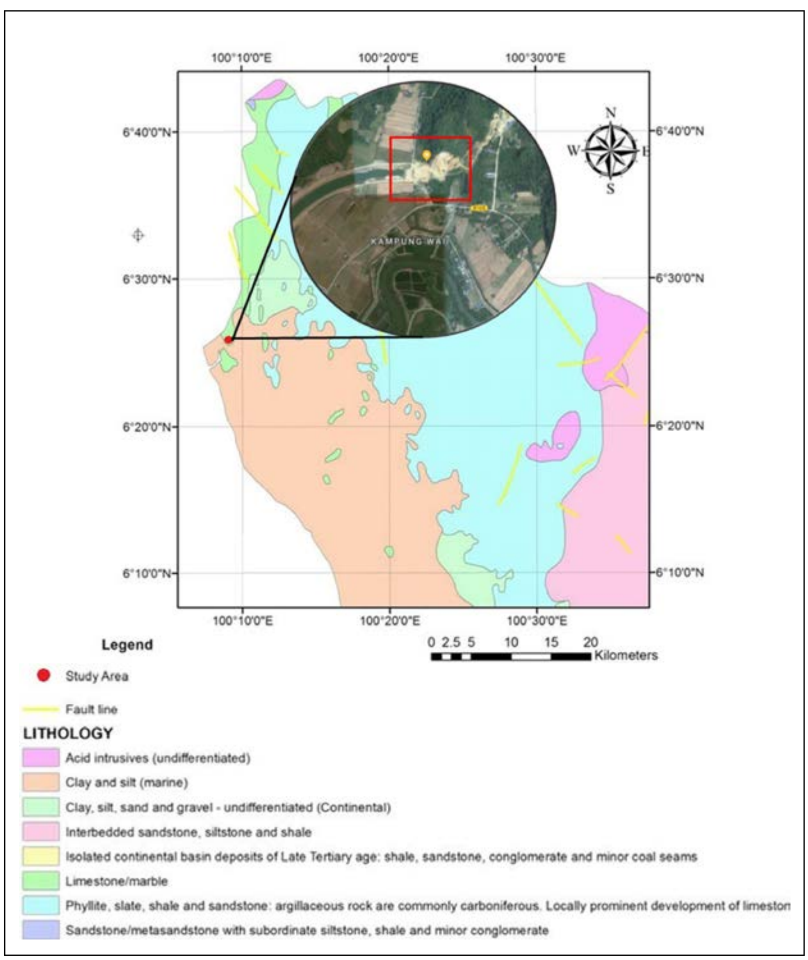

Figure 1: Study area and geological map (lithology) of study area and location.

some parts of the hills need to be excavated. The coordinates of the study area is 6.428794 latitude and 100.143884 longitude as shown in Figure 1. The lithology of the outcropping stratum of the study area is Setul Group (Figure 1). The Setul Group is characterised by a thick succession of bedded shelly limestone with minor intercalated bands of clastic and siliceous sedimentary rocks, conformably overlying the Machinchang Formation. The Setul Group is divided into several formations: Kaki Bukit Limestone, Tanjong Dendang Formation, Mempelam Limestone and Timah Tasoh Formation.

METHODOLOGY

UAV photogrammetry

Before commencing any operations on collecting data via UAV, a detailed site study was carried out to determine the size and the condition of the area of interest. The UAV with a mounted camera was used for slope mapping by taking aerial or side images of the slope. All the images were geo-tagged with the coordinates by the built-in GPS in the UAV. However, the coordinates received are not corrected and might have random errors. Hence, GCP was set up on the study area to measure the exact coordinates of the location using RTK-GNSS instrument in which the coordinates were auto-corrected by the nearest RTK base station. The coordinates were obtained using Real-Time Kinematic technique (RTK) derived from Global Navigation Satellite System (GNSS) in the Leica Viva CS10 controller equipped with SmartWorx Viva surveying software.

Selection of the mapping area on an interactive map, flying height of the UAV to capture images, the course angle of pathway and the percentage of front and side photos overlapped by using any flight planning application were made. For this study, DJI Ground Station Pro application was utilized. The percentage of overlapping photos is critical in producing an accurate sparse cloud of the study area. Front and side images overlapping ratio is 80% and 70% respectively. Waypoints were generated after all the settings were set, that shows the global position, distance covered, flying height above ground, number of images that will be captured, the estimated battery usage and the duration of the flying mission. Table 1 shows information of the flight mission at the rock slope.

The images captured were imported into the photogrammetric software Agisoft Photoscan Professional to process and align all the images accordingly with the use of feature matching algorithm. Feature matching is the advanced algorithm in Structure from Motion (SfM) software, and in this study, it is Agisoft Photoscan. Then bundle adjustment was carried out to build the dense cloud. Construction of 3D textured model, Digital Surface Model (DSM) and orthophoto were then processed from the dense point clouds. A summary of the photogrammetric procedure is shown in Figure 2.

3D and 2D limit equilibrium rock slope stability analysis

Rocscience Slide3 Version 2017 was used to analyse the 3D rock slope stability in this research. It is a 3D limit equilibrium slope stability program for evaluating the safety factor of 3D failure surfaces in soil or rock slopes. From the 3D rock slope stability analysis, a critical global minimum slip surface of the rock slope can be identified. Then, the 2D section of the global minimum slip surface can be extracted and analysed in a 2D analysis using probabilistic method where the least FoS analysed. The 2D analysis was carried in Rocscience Slide Version 2018 which is a 2D limit equilibrium slope stability software that evaluates the FoS of circular or non-circular failure surfaces of soil or rock slopes. It analyses the stability of slip surfaces using vertical slice or non-vertical slice limit equilibrium methods.

1- Build geometry

Since the rock slope geometry was created by using photogrammetry approach, the 3D textured model produced from Agisoft Photoscan Professional software in the (.obj) format was imported into Rocscience Slide3 2017 software. Then, the volume of the geometry of the rock slope was created by using the function “extended from the surface” as the geometry imported only presented the textured surface of the rock slope.

2- Export section plane from 3D geometry

Since the 3D model of the rock slope was produced and the critical global minimum slip surface of the rock slope was known from the 3D analysis, the cross-section

Table 1: Details of flight information at the rock slope.

Details of Flight Mission	
Date and time	6th February 2018, 11.00 a.m.
Area covered	12300 m^2
Distance covered	426 m
Altitude	70.0 m
Front Overlap Ratio	80 %
Side Overlap Ratio	70 %
Resolution	1.9 cm/pixel

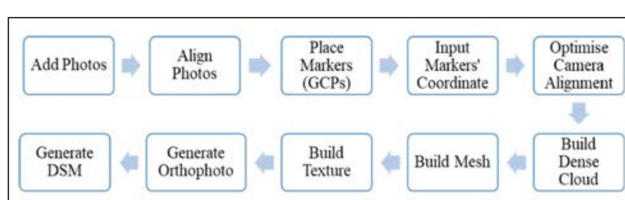

Figure 2: Flowchart of processing images in Agisoft Photoscan Professional.

of the plane was extracted in Rocscience Slide3 software and exported into Rocscience Slide software for 2D limit equilibrium slope stability analysis.

3- Limit equilibrium analysis method

Morgenstern-Price or general limit equilibrium (GLE) analysis method with half-sine inter-slice force function was used to analyse the rock slope stability. Figure 3 depicts the slice data of the Morgenstern-Price method. Interslice force inclination can vary with an arbitrary function (f(x)) as:

$T = f(x).\ \lambda.\ E$

where,

$f(x)$ = interslice force function that varies continuously along the slip surface,

λ = scale factor of the assumed function.

The method suggests assuming any type of force function, for example half-sine, trapezoidal or user defined. The relationships for the base normal force (N) and interslice forces (E, T).

$$F_f = \sum\{c'l + (N - ul)\tan\phi'\}\sec\alpha] \,/\, \sum\{W-(T_2-T_1)\}\tan\alpha + \sum(E_2-E_1)$$

$$F_f = \sum(c'l + (N - ul)\tan\phi') \,/\, \sum W \sin\alpha$$

4- Define rock slope material

The materials of the rock slope must be well defined with its strength. Different failure criteria can be selected to define the strength of the materials. Intact rock mass was defined using Generalized Hoek-Brown Failure Criterion. Since rock mass consists of discontinuities, generalized anisotropic was used to define the orientations of the anisotropic plane in the rock slope as displayed. The weak joint was defined by Mohr Coulomb Failure Criterion.

5- Assign material

After defining all the rock materials, the correct material must be assigned to the rock geometry. In this study, the anisotropic plane was assigned to the rock slope as it has taken into consideration the strength of the rock mass as well as the strength of the weak joint.

6- Deterministic and probabilistic analysis

Deterministic analysis renders a single value of FoS by assuming the values of all model input parameters are exactly known. Nevertheless, rock slope is heterogeneous in reality, and the parameters are varying at different locations. Hence, probabilistic method is useful in the rock slope stability analysis as it can determine the effect of uncertainty or variability of input parameters on the results of the slope stability analysis. Statistical distributions can be assigned to the input parameters. The sampling method determines how the statistical input distributions for the random variables defined for a probabilistic analysis will be sampled. Monte Carlo sampling method was utilized. The Monte Carlo sampling technique uses random numbers to sample from the input data probability distributions and is normally used in geotechnical engineering. The outcome will be the global minimum surface with deterministic FoS, mean FoS of the probabilistic method, probability of failure and reliability index. Global Minimum Slip Surface is the 3D slip surface with the lowest factor of safety, for a given analysis method, of all slip surfaces analyzed. The Global Minimum Slip Surface and Factor of Safety is automatically displayed when you view analysis results.

7- Slip surface search method

Cuckoo Search method was applied in this study for locating the critical slip surfaces of the rock slope. It is a stochastic search method in which randomness is introduced in the algorithm. It requires no user defined search objects as the algorithm will run automatically when the computation

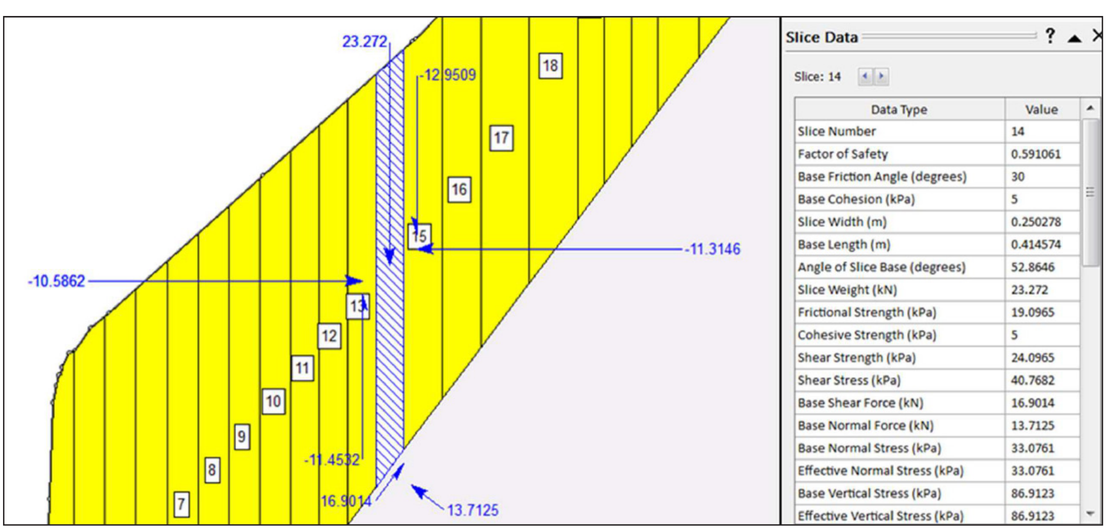

Figure 3: Slice data from Morgenstern-Price method from Rocscience Slide 2017 software.

of results start. Ellipsoidal surface was used in Cuckoo Search. The search commences with a random population of "n" failure surfaces with each surface being assigned to a nest. For each nest, a new random surface based on its current surface is generated. These new surfaces are compared with the solution in a random nest. The number of nests in Cuckoo Search implies different paths that will be used to explore the search region. 20 different paths are sufficient. Due to the stochastic nature of Cuckoo Search, it tends to escape local minimum and is considered as global optimization method. Normally, Cuckoo Search is combined with surface optimization as it is more efficient in local search. Surface Altering optimization is a powerful tool in rendering lower FoS by modifying geometry of a given surface. The input surface is converted to a spline approximation. Then, the control points defining the surface are modified in a way that minimizes the FoS. The process stops when either the maximum number of iterations is reached or when the optimization does not make any further progress. The non-circular slip surface type was selected due to the anisotropic plane (discontinuity) in the rock slope.

8- Compute 2D and 3D rock slope stability result

The deterministic analysis for 3D FoS and probabilistic analysis for 2D FoS was computed. Outcome will be the global minimum slip surface and the FoS of the section of the rock slope for 2D and the entire rock slope for 3D.

RESULTS AND DISCUSSION

Rock slope stability assessment for deterministic approach was carried out for 3D LEM method. Besides, cross section extracted from 3D rock geometry respectively were analyzed by deterministic and probabilistic method in 2D. In 3D (Rocscience Slide3) and 2D (Rocscience Slide 2018) rock slope stability analysis, all the settings and parameters are kept the same. Morgenstern-Price or GLE method was used to analyse the stability as it involved horizontal and vertical force equilibrium as well as moment equilibrium. The slip surface was searched using Cuckoo Search Method with surface altering optimization. All the rock input parameters for both cases are the same except the existence of anisotropic plane. The mean dip / dip direction obtained was used as an input for the value of the anisotropic plane where it causes a weakness in the strength of the rock slope.

FoS of the 3D rock geometry were analysed with anisotropic plane and the input of major discontinuity sets of mean dip / dip directions (043°/189 and °046°/172°). The least deterministic FoS of the entire rock slope in 3D analysis is 0.908 as shown in Figure 4. This value indicates that the rock slope is unstable and tends to fail at any time. Figure 5 shows the FoS of the 2D cross-section at the x-axis of the 3D rock slope which is the global minimum slip surface (maroon) as depicted in Figure 4. The least FoS analysed by deterministic method is 0.612. Contrarily, the least FoS analysed by probabilistic method is 0.361. The mean probabilistic FoS is 0.623. The probability of failure (PF) as indicated is 100% with reliability index (RI) less than 1.

The FoS of rock slope in 3D and 2D analysis is tabulated in Table 2. Deterministic FoS is the safety factor calculated for the global minimum slip surface from the regular rock slope stability analysis when all input parameters are exactly equal to their mean values. Contrarily, the probabilistic method is carried out according to the normal distribution of the rock parameters on the global minimum slip surface. The mean FoS obtained from probabilistic analysis is the average safety factor of all the FoS calculated for the global minimum slip surface. Generally, the mean FoS from probabilistic analysis should be nearly equal to the deterministic FoS. However, a lower minimum FoS is obtained from the probabilistic method compared to deterministic method because the analysis method considers the randomness of the parameters in analyzing the rock slope, rendering the worst case among all the slip surfaces.

Besides, 3D deterministic analysis gives higher FoS than that of 2D deterministic analysis. This is mainly because the 3D failure surface does not consider the weak rock surface only, but also strong ones, neglecting the

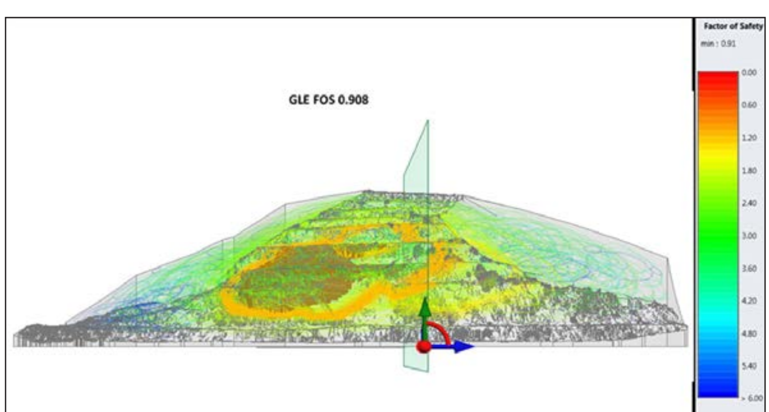

Figure 4: FoS of rock slope with anisotropic plane in 3D.

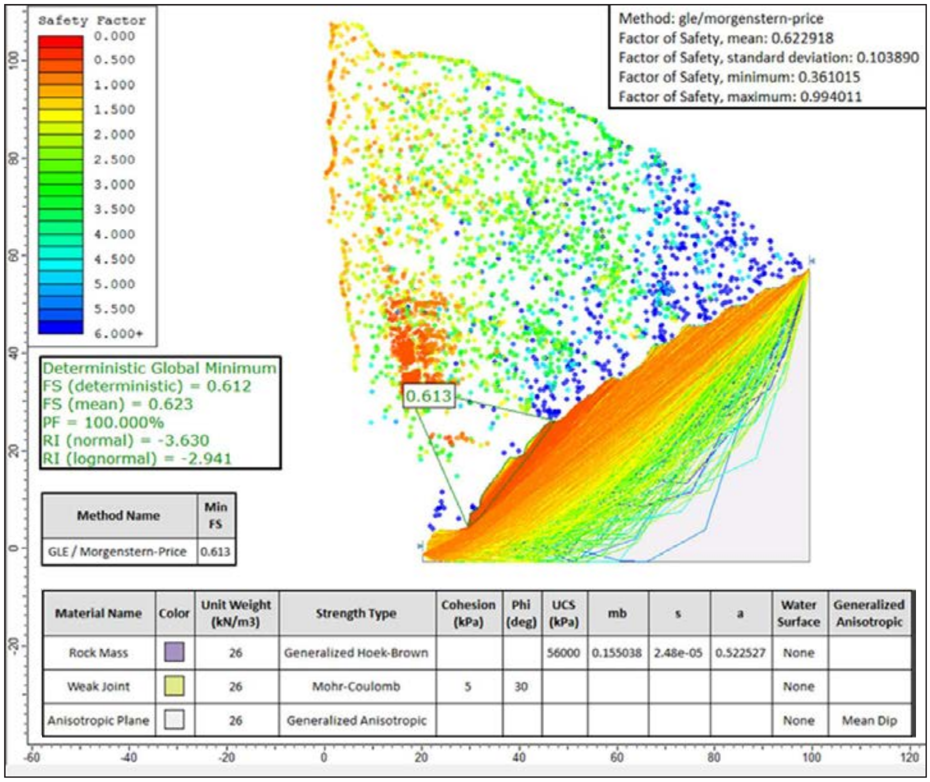

Figure 5: FoS of cut section with anisotropic plane in 2D.

Table 2: Rock slope stability FoS in 3D and 2D analysis.

Least deterministic FoS in 3D analysis	FoS in 2D analysis		
	Global Minimum Surface		
	Deterministic (Least)	Probabilistic	
		Mean	Least
0.908	0.612	0.623	0.361

over-conservative simplification assumed within the 2D sections. FoS of the slope indicates the real site situation at situation where some parts of the rock slope tend to fail following the weak discontinuity plane. Most of the parts failed through planar sliding because the slope face is daylighting (Figure 6).

Figure 6: Site condition on posibility of failure through planar sliding.

CONCLUSION

3D textured model geometry of the rock slope produced was used for rock slope stability analysis together with the orientations extracted act as the variables. The outcome shows that the probabilistic method of limit equilibrium analysis renders a more conservative FoS compared to deterministic method. FoS from probabilistic method is 0.336 whereas 0.591 from deterministic method. Therefore, probabilistic method should be used in the analysis with considering the anisotropic plane since the rock slope is heterogeneous, having various discontinuities patterns, unpredictable and anisotropic.

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REFERENCES

Dall'Asta, E., Forlani, G., Roncella, R., Santise, M., Diotri, F. & Morra di Cella, U., 2017. Unmanned Aerial Systems and DSM matching for rock glacier monitoring. ISPRS Journal of Photogrammetry and Remote Sensing, 127, 102-114. doi:10.1016/j.isprsjprs.2016.10.003.

Hoek, E., 2007. Practical Rock Engineering. Retrived from https://www.rocscience.com/assets/resources/learning/hoek/Practical-Rock-Engineering-Full-Text.pdf.

Johnson, K., Nissen, E., Saripalli, S., Arrowsmith, J. R., McGarey, P., Scharer, K., Williams, P., Blisniuk, K., 2014. Rapid mapping of ultrafine fault zone topography with structure from motion. Geosphere, 10(5), 969-986. doi:10.1130/GES01017.1.

Raghuvanshi, T. K., 2017. Plane failure in rock slopes - A review on stability analysis techniques. Journal of King Saud University - Science, 31(1), 101–109. doi:10.1016/j.jksus.2017.06.004.

Tahar, K. N., 2015. Multi rotor UAV at different altitudes for slope mapping studies. In International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives. doi:10.5194/isprsarchives-XL-1-W4-9-2015.

Tang, H., Yong, R. & Ez Eldin, M. A. M., 2017. Stability analysis of stratified rock slopes with spatially variable strength parameters: the case of Qianjiangping landslide. Bulletin of Engineering Geology and the Environment, 76(3), 839-853. doi:10.1007/s10064-016-0876-4

Tannant, D. D., 2015. Review of Photogrammetry-Based Techniques for Characterization and Hazard Assessment of Rock Faces. International Journal of Georesources and Environment, 1(2), 76–87. doi:10.15273/ijge.2015.02.009.

Tung, W. Y., Nagendran, S. K. & Mohamad Ismail, M. A., 2018. 3D rock slope data acquisition by photogrammetry approach and extraction of geological planes using FACET plugin in CloudCompare. In IOP Conference Series: Earth and Environmental Science. doi:10.1088/1755-1315/169/1/012051.

Turner, D., Lucieer, A. & de Jong, S. M., 2015. Time series analysis of landslide dynamics using an Unmanned Aerial Vehicle (UAV). Remote Sensing, 7(2), 1736–1757. doi:10.3390/rs70201736.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J. & Reynolds, J. M., 2012. Structure-from-Motion photogrammetry : a low -cost, effective tool for geoscience applications, Introduction. Geomorphology, 179, 300–314. doi:10.1016/j.geomorph.2012.08.021.

Zhao, H., Li, Z. & Kong, C. S., 2016. Probabilistic method to determine the overall rock block failure based on failure mode. Engineering Transactions, 64(1), 105-113. doi:10.1251/bpo103.

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