ROCK SLOPE STABILITY ASSESSMENT USING PHOTOGRAMMETRIC MAPPING AND LIMIT EQUILIBRIUM METHOD

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SCHOOL OF CIVIL ENGINEERING
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ROCK SLOPE STABILITY ASSESSMENT USING PHOTOGRAMMETRIC MAPPING AND LIMIT EQUILIBRIUM METHOD

By

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I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

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Date:

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(Signature of Examiner)

Name of Examiner:

Date:  
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ABSTRAK

Penggalian cerun batu untuk pembangunan infrastruktur seperti lebuhraya dan saluran air tidak dapat dilakukan. Oleh itu, pencirian cerun batu dan tanggungan reka bentuk yang betul harus dilakukan untuk memastikan kestabilan cerun batu. Penggunaan teknik kajian garis imbasan dalam pengukuran orientasi ketakselanjaran di cerun batu mengambil masa panjang dan amat mencabar disebabkan akses yang terhad. Struktur dari gerakan (SfM) yang menggunakan UAV merupakan satu cara yang cepat dan murah untuk melakukan pemetaan tinjauan tentang pencirian geoteknikal cerun batu berbanding dengan pengimbasan laser daratan (TLS). Gambar yang ditangkap dan diproses melalui pelarasan bundle dengan titikan kawalan tanah (GCP) dapat menghasilkan titik awan padat, model 3D, model digital permukaan (DSM) dan gambar ortho dengan ketepatan dalam lingkungan sentimeter. Satu kajian telah dilakukan di cerun batu di Projek Lencongan Banjir Barat Timah Tasoh, Perlis. Titik awan padat diimport ke dalam CloudCompare untuk mengekstrak data permukaan geologi. Data permukaan geologi tersebut adalah amat tepat kerana jurang dengan data diukur secara manual adalah dalam lingkungan 7°. Seterusnya, dengan menggunakan data ketakselanjaran, analisis kinematik menunjukkan bahawa cerun batu mempunyai 15.40% risiko dalam slaid planar, 7.16% dalam slaid bagi dan 1.33% dalam guling lenturan. Kestabilan cerun batu dianalisis dengan kaedah keseimbangan had (LEM) deterministik dalam 3D dan 2D serta LEM probabilistik dalam 2D. Geometri cerun batu, orientasi ketakselanjaran dan parameter yang diperolehi daripada pangkalan data digunakan dalam analisis. Dengan kaedah deterministik, FoS diperolehi daripada 3D (0.908) adalah lebih tinggi daripada 2D (0.591). FoS probabilistik dalam 2D adalah
rendah (0.336) berbanding dengan deterministik (0.591). Kaedah probabilistik adalah lebih konservatif kerana mengambil kira ciri-ciri kepelbagaian dalam jisim batuan.
ABSTRACT

Rock slope excavation is unavoidable for the infrastructure development in our country such as expressway and water channel. Hence, a proper rock slope characterization and support design has to be carried out to ensure the stability of the rock slope, preventing hazardous events. Measuring discontinuity orientation in the rock slope by traditional scanline survey is time consuming and challenging due to the accessibility issue. Structure from motion (SfM) photogrammetry using UAV permits a fast and inexpensive way to do survey mapping for geotechnical characterization of rock slope compared to terrestrial laser scanner (TLS). Images that are captured and going through bundle adjustment with ground control points (GCPs) render within centimetre accuracy of dense point cloud, 3D model, orthophoto and digital surface model (DSM).

A case study was conducted at the rock slope of Projek Lencongan Banjir Barat Timah Tasoh, Perlis. Dense point cloud is imported into CloudCompare to extract the geological planes. The discontinuities extracted are reliable and accurate as they are within 7° of the data measured manually. By using discontinuity data, the kinematic analysis shows that the rock slope has 15.40% of risk in planar sliding, 7.16% in wedge sliding and 1.33% in flexural toppling. Rock slope stability is analysed by deterministic Limit Equilibrium Method (LEM) in 3D and 2D and probabilistic LEM in 2D, utilising the 3D rock slope model geometry and orientation discontinuity extracted as well as the parameters obtained from the database. By comparing deterministic method, FoS obtained from 3D analysis (0.908) is higher than 2D analysis (0.591). On the other hand, by comparing probabilistic and deterministic method in 2D analysis, probabilistic method renders lower FoS (0.336) than deterministic method.
Probabilistic method is more conservative as it considers the heterogeneity characteristic of the rock mass.
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<thead>
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<th>Full Form</th>
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<tbody>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
</tr>
<tr>
<td>UAS</td>
<td>Unmanned Aircraft System</td>
</tr>
<tr>
<td>SfM</td>
<td>Structure from Motion</td>
</tr>
<tr>
<td>TLS</td>
<td>Terrestrial Laser Scanner</td>
</tr>
<tr>
<td>RTK</td>
<td>Real Time Kinematic</td>
</tr>
<tr>
<td>GCP</td>
<td>Ground Control Point</td>
</tr>
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<td>CP</td>
<td>Check Point</td>
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<td>Global Positioning System</td>
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<td>Global Navigation Satellite System</td>
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<td>RTK</td>
<td>Real-Time Kinematic</td>
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<tr>
<td>CS</td>
<td>Cuckoo Search</td>
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<td>RMSE</td>
<td>Root Mean Square Error</td>
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<td>UTM</td>
<td>Universal Testing Machine</td>
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<td>UCS</td>
<td>Uniaxial Compressive Strength</td>
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<td>Geological Strength Index</td>
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<td>Disturbance Factor</td>
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<td>Limit Equilibrium Analysis</td>
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<td>Factor of Safety</td>
</tr>
<tr>
<td>PF</td>
<td>Probability of Failure</td>
</tr>
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<td>RI</td>
<td>Reliability Index</td>
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CHAPTER 1

INTRODUCTION

1.1 Background

Malaysia is a mountainous country where almost half of it is over 150m above mean sea level and covered by granite, limestone, stratified rocks, igneous rocks, alluvium, etc. Nation’s development involving building of infrastructure work such as expressway through the mountains is unavoidable as for the improvement of the connectivity and accessibility between one city and another. Hillside development has also increased for the past three decades in densely populated cities like Kuala Lumpur and Penang due to the limited flat and undulating lands in the cities. Nowadays, people would like to move to hilly area for the exclusivity, fresher air and better scenery (Gue and Wong, 2009). Besides, the excavation of rock slopes for irrigation and water channel is necessary to prevent flood occurrence in the area. Nonetheless, without proper design on the geotechnical aspect in the hilly terrain, it will be a hazard to the community. Moreover, geo-hazard incidents like rock slab detachment and rock falls might occur as a result of weathering processes and discontinuity factors characterized mainly by geological structure conditions such as jointing, fractures and day lighting of discontinuities. These geological hazards will affect the vulnerability of development in the encompassing areas. The impact of a rock fall can also affect its surrounding in which the air blast resulting from the fallen rock debris can be felt at a distance that is much further from the catastrophe area which could affect nearby buildings (Goh et al., 2017). Hence, it is crucial to carry out confirmatory geological slope mapping of the exposed slopes during construction of high cut slopes to detect any geological discontinuities that may cause potential failure mechanisms (Gue and Wong, 2009).
Rock mass is a high strength material if it is homogeneous and isotropic. Nevertheless, in reality, rock mass is heterogeneous and anisotropic since it has a lot of discontinuities and uncertainties due to the stresses induced by movement of tectonic plates and weathering effect. A discontinuity will manifest most commonly in a rock mass as a joint, fault, bedding surface, or blast damage. The orientations of the discontinuities contribute to the weakness in strength of the rock mass. Thus, it is vital to identify the discontinuity data in the rock slope.

There are many ways available to obtain the rock slope discontinuity data. 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 datasets 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 ease 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 are used widely in geomorphological environments including river bed topography (Rusnák et al., 2018), glaciology (Dall’Asta et al., 2017;
Rossini et al., 2018), volcanology (Gomez and Kennedy, 2018), landslide (Gabrieli et al., 2016; Stumpf et al., 2015, 2014; Turner et al., 2015) and rock slope mapping for discontinuity characterization (Tannant, 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.

In rock slope, plane sliding, wedge sliding and flexural toppling are common modes of failures due to the discontinuity in the rock mass. Plane mode of failure generally occurs in slice formed by stratified sedimentary and meta-sedimentary rock formations. The plane failure in rock slope occur when a structural discontinuity plane dips or daylight towards the valley at an angle smaller than the slope face angle and greater than the angle of friction of the discontinuity surface (Tang et al., 2017). The strike of the potential discontinuity surface must be nearly parallel to the slope face. Tension crack must be present in the upper portion of the slope. Under such conditions the rock mass which rests on the discontinuity plane will slide down the slope when shearing stresses becomes more than the resisting forces (Hoek and Bray, 1981). Hence, by knowing the discontinuity orientations of the rock slope, the risk of rock failure in various modes can be determined.

There are two ways in analysing 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 etc. (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).

1.2 Problem Statement

The development of infrastructure work such as road and highway constructions involving deep cutting into the slope is unavoidable as it connects two cities with the shortest distance and traveling time. Besides, the need of development on hilly areas for building and residential purpose has also increased and these lead to the concern of safety and stability of the slope for the public. Hence, rock slope stability is concern about analyzing the structural fabric of the site to determine if the orientation of the discontinuities could result in instability of the slope under consideration. Nevertheless, in rock slopes, due to the structure of the cutting surface, rock mass typically exhibits
strong random properties, such as the structure of the surface geometry and mechanical parameters, resulting in a high degree of rock mass uncertainty. As a result, one of the greatest challenges for rock slope stability analysis is the selection of representative values from widely scattered discontinuity data. Hence, rock slope stability analysis using deterministic method is unsuitable. Deterministic analysis based on the factor of safety concept, requires a fixed representative value for each parameter without regard to the degree of uncertainty. Therefore, the deterministic analysis that is so common in engineering geology studies, fails to properly represent stochastic properties of discontinuities.

Generally, rock masses are heterogeneous and unpredictable as they contain discontinuities such as orientation, size, aperture, surface conditions (roughness and alteration), and frequency. Discontinuity plays an important role in the strength, stability, deformability and permeability of the rock mass. Besides, the soil material in the anisotropic plane will weaken the rock mass as well. Thus, the description of discontinuities in rock mass must be accurate to enhance the quality of geological input data for an effective geotechnical assessment. The ability of overcoming bias as well as the amount of data collected will have an effect on the discontinuity spacing and trace length measurements (Priest and Hudson, 1981). Traditional ways of characterizing the rock slope such as scanline survey, cell mapping and rapid face mapping which use a compass, an inclinometer and a measuring tape, have several disadvantages because rock mass exposures often have limited accessibility which affects the choice of sampling location. As a result, the site investigation is bias, hazardous, time consuming and expensive (Torres, 2008).

TLS and SfM photogrammetry are the current technologies available for topography mapping to produce rock slope geometry. However, the cost of acquisition
of TLS is expensive. Furthermore, many researches using TLS have been done and showed that the results are coherent with the results obtained from the traditional methods. However, there is less research on using UAV for rock slope mapping by SfM method. Thus, SfM photogrammetry using unmanned Aerial Vehicle (UAV), an alternative method to produce 3D dense point clouds will be carried out.

1.3 Objective

The objectives of this study are:

1. To determine the accuracy of using photogrammetry approach for slope mapping with and without ground control points (GCPs).

2. To determine the rock slope geometry and its geological structure using photogrammetry approach with the bundle adjustment of GCPs.

3. To verify the rock slope discontinuities orientations extracted digitally by the least square fitting algorithm in FACET plugin in CloudCompare with the data measured manually using scanline survey method.

4. To access the factor of safety (FoS) of the rock slope based on various discontinuities pattern using deterministic Limit Equilibrium Method (LEM) in 3D and 2D analysis and probabilistic LEM in 2D analysis.
1.4 Scope of Work

The scope of work is focusing on the accuracy assessment of photogrammetry approach processed with and without Ground Control Points (GCPs) by mapping a gentle slope at various flying heights. A quad copter (UAV) is used to capture the images of the slope. The dataset is processed with and without GCP where the GCP coordinates are obtained from Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) instrument. Then, a rock slope is mapped by following the same procedure as mapping the gentle slope at an optimum flying height. The photogrammetric data are processed with GCP to obtain the rock slope geometry and geological structure. The dip / dip direction of the discontinuity present in the rock slope is extracted digitally. Kinematic analysis is conducted using the orientation data to determine the critical percentage of planar sliding, wedge sliding and flexural toppling failure mode. Besides, rock slope stability analysis using limit equilibrium method is conducted to determine the critical safety factor of the rock slope by inputting the orientations extracted as the anisotropic plane and the rock mass parameters obtained from a database. Deterministic method with slip surface analyzing method, cuckoo search is carried out on the 3D rock slope. Then, by identifying the global minimum slip surface of the rock slope geometry in 3D, the critical cut section is extracted to analyse in 2D. Since the rock mass has uncertainty and variability, probabilistic method is used to analyse the 2D cut section. The scope of work is to achieve the main objectives of this research.
1.5 **Dissertation Outline**

This thesis consists of five chapters. Chapter 1 is the Introduction where this chapter provides an overview of the thesis, the problem statement, followed by the objectives of this research and the scope of work of this research. Chapter 2 is the Literature Review. This chapter provides critical theoretical and conceptual understanding about the research. The previous works conducted by other researchers serve as basic knowledge for the study. Next is chapter 3: Methodology. This chapter discusses the study area and comprehensive descriptions on the overall methods that have been applied in this study. The flow will be viewed in detail to facilitate the understanding on the execution of the research. Chapter 4 is about results and discussion. This chapter involves data processing, analysis, interpretation and evaluation of the rock slope stability by using software application. Lastly, chapter 5 is Conclusion. This chapter summarizes and concludes the findings in this research. All the limitations of the study and assumption that have made throughout the study are listed. Some suggestions and recommendations for further study of this topic are clearly listed in this chapter. The overview structure of the thesis is depicted in Figure 1.1.
Chapter 1: Introduction
- Background of the Study
- Problem Statement
- Objectives
- Scope of Work

Chapter 2: Literature Review

Chapter 3: Methodolody
- Slope mapping
- Rock slope mapping
- Photogrammetric processes of slope with and without GCP at various flying heights
- Photogrammetric processes of rock slope
- Rock slope discontinuity extraction
- Kinematic and sensitivity analysis of rock slope
  - Plane Sliding
  - Wedge Sliding
  - Flexural Toppling
- Rock slope stability analysis
  - Limit Equilibrium Method (LEM) – Morgenstern-Price Method
  - Generalised Hoek-Brown Failure Criterion
  - Generalised Anisotropic
  - Slip surface analysis method – Cuckoo Search
  - Deterministic Method (in 3D and 2D)
  - Probabilistic Method (in 2D)

Chapter 4: Results and Discussion
- Accuracy Assessment of Photogrammetric Data with GCP and without GCP
- Rock geometry and geological structure
- Discontinuity orientation (Dip / Dip Direction) of the Rock Slope
- Probability of Failure of Rock Slope in Kinematic Analysis
- Factor of Safety of the Rock Slope

Chapter 5: Conclusion
- Conclusion of the study
- Limitations of the study
- Recommendations of the study

Figure 1.1: Structure of the thesis.
CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Literature review is predominant for any research. It includes the previous work conducted by other researchers. This chapter reviews the application of Structure from Motion (SfM) photogrammetry and its accuracy on the research work. The accuracy of the technique of getting the exact location, Real Time Kinematic (RTK) is discussed. Besides, this chapter also discusses the previous work on extracting discontinuity of rock mass automatically. Moreover, the rock slope stability analysis method is discussed.

2.2 SfM Photogrammetry

Photogrammetry is a measurement technique that uses light rays captured by a camera. Structure from Motion (SfM) is an image processing technique that was originally developed for computer vision applications. Some fundamental mathematics used in SfM techniques, including camera pose estimation, camera calibration, triangulation, and bundle adjustment, were adapted from photogrammetry. Using multiple overlapping images as shown in Figure 2.1, the SfM algorithms can estimate the camera pose parameters and generate sparse point-clouds. Further image processing using multiple view stereo can generate a dense point cloud once the correspondence among multiple camera locations has been established (Tannant, 2015). Image processing using SfM has been implemented in commercial software such as Agisoft Photoscan Professional. Unmanned aerial vehicle (UAV) can be considered as a low-cost alternative to the classical manned aerial photogrammetry. UAV, capable of
performing the photogrammetric data acquisition by capturing images with digital cameras, can fly in manual, semi-automated, and autonomous modes. Following a typical photogrammetric workflow, 3D results like digital surface or terrain models, contours, textured 3D models, vector information, etc. can be produced, even on large areas (Nex and Remondino, 2013). Agüera-Vega et al. (2018) claims that the development of UAV photogrammetry over the last decade has allowed terrain that is challenging for humans to access to be captured at very high spatial and temporal resolutions. UAV images can produce slope map of the real site study area with highly accurate results (Tahar, 2015).

Figure 2.1: Method of capturing images for photogrammetry (Ibraheem et al., 2014).

2.2.1 Reliability of SfM Photogrammetry

Martin et al. (2007) has conducted a research on the comparison of the accuracy of the three-dimensional digital models of a 55m high rock slope derived from the ground-based LiDAR and digital photogrammetry survey. Canon 5D digital Single Lens Reflex camera with a 35mm Canon fixed focus lens with focus set at infinity and f/8 aperture was used to capture the images of the rock slope for photogrammetry. They
concluded that both survey methods gave similar DEM results that would be suitable for rock engineering problems as well as for extracting the orientation data of geological features. The overall error for LiDAR model is 138mm whereas for photogrammetry model is 98mm. This indicates photogrammetry approach renders good quality results. Although the density of the point cloud from LiDAR survey is denser which means smaller features could be extracted, it is not considered to be a practical advantage. The photogrammetry survey is quicker to conduct in the field compared to the LiDAR survey.

Another research was conducted by Wilkinson et al. (2016) on the comparison between the usage of TLS and SfM photogrammetry for the ground-based digital outcrop. The study was conducted on the outcrops from North East England and the United Arab Emirates. A 12 megapixel Nikon D300 with Nikon AF-S DX Nikkor 10–24 mm f/3.5–4.5G ED and Nikon AF-S DX Nikkor 55–200 mm f/4.5–5.6G IF-ED VR lenses camera were used for SfM. They claimed that both TLS and SfM are viable methods for use in the field, although no single technology is universally best suited to all situations. Table 2.1 shows the practical considerations and operating conditions of TLS and SfM where each method has clear advantages. The suitability of each method depends on the aim of the work, the expected outcome, the nature of the outcrop, and the prevalent operating conditions. Compared to LiDAR point clouds, RMSE of the photogrammetric point clouds generally did not exceed 0.2m for the reconstruction of the entire landslide and 0.06 m for the reconstruction of the main scarp. The SfM technique currently remains less precise than TLS but provides spatially distributed information at significant lower costs and is, therefore, valuable for many practical landslide investigations (Stumpf et al., 2015).
Table 2.1: Practical considerations of TLS and SfM photogrammetry for data acquisition (Wilkinson et al., 2016).

<table>
<thead>
<tr>
<th></th>
<th>Terrestrial Laser Scanner (TLS)</th>
<th>Structure from Motion (SfM) photogrammetry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Typical Cost</strong></td>
<td>High ($50k – $200k)</td>
<td>Low ($650 – $10k)</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>High (15 – 50kg)</td>
<td>Low (2 – 15kg)</td>
</tr>
<tr>
<td><strong>Package size for transport</strong></td>
<td>Large (small suitcase sized)</td>
<td>Small (daypack sized)</td>
</tr>
<tr>
<td><strong>Number of operators</strong></td>
<td>1+</td>
<td>1+</td>
</tr>
<tr>
<td><strong>Level of operator training</strong></td>
<td>Moderate</td>
<td>Moderate – high</td>
</tr>
<tr>
<td><strong>Certainty of success (for critical application)</strong></td>
<td>High (results available immediately)</td>
<td>Moderate (final results known after images processed)</td>
</tr>
<tr>
<td><strong>Immediate results in the field</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Acquisition time</strong></td>
<td>Comparable with SfM</td>
<td>Comparable with TLS</td>
</tr>
<tr>
<td><strong>Precision</strong></td>
<td>High (2 – 8mm, mostly independent of range)</td>
<td>Ultra high to ultra-low (image resolution and range dependent)</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>≈ 5cm (GPS dependent)</td>
<td>≈ 5cm (GPS dependent)</td>
</tr>
<tr>
<td><strong>Detail (point spacing)</strong></td>
<td>Low – high (range dependent)</td>
<td>Low – high (range dependent)</td>
</tr>
<tr>
<td><strong>Internal consistency</strong></td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>Processing time</strong></td>
<td>Low (minutes to hours)</td>
<td>High (hours to days, dependent on workstation and desired detail)</td>
</tr>
<tr>
<td><strong>Additional data</strong></td>
<td>Laser reflection intensity per point</td>
<td>Normal to outcrop surface per point</td>
</tr>
<tr>
<td><strong>Versatility in a range of applications</strong></td>
<td>High</td>
<td>Moderate (dependent on operator experience)</td>
</tr>
<tr>
<td><strong>Ability to resume survey at a later time</strong></td>
<td>High</td>
<td>Moderate (dependent on similar outcrop appearance)</td>
</tr>
<tr>
<td><strong>Multi-day survey, without mains power</strong></td>
<td>Moderate (extra batteries relatively expensive, bulky, and heavy)</td>
<td>High (extra batteries relatively cheap, small and light)</td>
</tr>
<tr>
<td><strong>Remote operation for temporal survey</strong></td>
<td>Yes</td>
<td>No; operator driven</td>
</tr>
<tr>
<td><strong>Automated acquisition</strong></td>
<td>Yes</td>
<td>No; operator driven</td>
</tr>
<tr>
<td><strong>Dependence on data from other sources</strong></td>
<td>Low (GNSS provides orientation and location)</td>
<td>Moderate (GNSS provides scale, orientation, and location)</td>
</tr>
<tr>
<td><strong>Depreciation of equipment value</strong></td>
<td>Low</td>
<td>Low–moderate</td>
</tr>
<tr>
<td><strong>Ruggedness</strong></td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>General availability</strong></td>
<td>Low</td>
<td>Moderate–high</td>
</tr>
<tr>
<td><strong>Ease of service and availability of replacement parts</strong></td>
<td>Low–moderate</td>
<td>Moderate–high</td>
</tr>
<tr>
<td><strong>Equipment used in fieldwork for other purposes?</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Ease of transport, import and/or export</strong></td>
<td>Low - moderate</td>
<td>High</td>
</tr>
</tbody>
</table>

1For the acquisition of data for rigorous quantitative analysis.
2The ability of the operator to review the acquired data in 3D before leaving the field.
3To consistently provide quality data for rigorous quantitative analysis.
4A measure of how much free time an operator has during the survey for other tasks, such as sample collection.
5TLS equipment must usually be returned to the manufacturer for servicing or part replacement by a specialist. SfM uses widely available camera equipment that can be serviced or replaced worldwide. Note: GNSS—Global Navigation Satellite System.
Mapping fault zone topography in areas of sparse or low-lying vegetation using SfM and LiDAR was conducted. At 0.1km² alluvial fan on the San Andreas Fault, the closest point vertical distances of SfM (point cloud density > 700 points/m²) to LiDAR (much sparser point cloud density, 4 points/m²) is less than three centimeter. On the other hand, at 1km section of the 1992 Landers earthquake scarp, the closest point vertical distances of SfM to LiDAR is less than six centimeter. This concludes that SfM greatly facilitates the imaging of subtle geomorphic offsets related to past earthquakes as well as rapid response mapping or long-term monitoring of faulted landscapes (Johnson et al., 2014). In short, SfM photogrammetry can produce a good quality and high accuracy of photogrammetric outputs which is comparable to TLS.

2.2.2 Application of SfM Photogrammetry

Photogrammetry has been widely used for more than a century for different purposes. Its surveys are being increasingly used to collect high resolution airborne imagery in a wide variety of environmental and geomorphological environments.

Uysal et al. (2015) has conducted a research on using UAV to map a five hectare area. Accuracy of the Digital Elevation Model (DEM) was evaluated with 30 check points and obtained 6.62 cm overall vertical accuracy from an altitude of 60 m. This concludes that it is possible to use the SfM Photogrammetry data as map producing, surveying, and some other engineering applications with the advantages of low-cost, time conservation, and minimum field work. The SfM technique can also be applied in glaciology. An accuracy of 17cm was achieved for the generation of DSM and orthophoto of glacial morphology from SfM techniques (Rossini et al., 2018). Dall’Asta et al. (2017) also discovered that the RMSE differences found on twelve Check Points were about 4 cm in horizontal and 7 cm in elevation. Agüera-Vega et al.
(2018) utilizes the SfM photogrammetry in topography mapping. They collected two different image datasets by tilting the camera horizontally and at 45°. The best accuracies achieved were RMSE equal to 0.053 m, 0.070 m and 0.061 m in X, Y and Z direction respectively. Turner et al. (2015) uses UAV to collect a time series of high-resolution images over four years at seven epochs to assess landslide dynamics. The SfM photogrammetry applied create DSM of the landslide surface with an accuracy of 4-5cm in the horizontal and 3-4cm in the vertical direction. Besides, landslide study using SfM was also conducted by Carvajal et al. (2012). Md4-200 micro drones with an on-board calibrated camera 12 Megapixels Pentax Optio A40 was used in the study. The accuracy of the products is 0.049m for planimetric errors and 0.108m for altimetric errors. Tannant (2015) utilises SfM in steep rock slope mapping. The theoretical coordinate accuracy in the model was approximately 20 mm. This is more than adequate to characterize many geometric features of relevance to the wedge failure, which had a height and width of roughly 15m. Besides, the application of SfM photogrammetry was conducted in various fields such as landslide (Gabrieli et al., 2016; Niethammer et al., 2010; Peterman, 2015; Stumpf et al., 2015, 2014), rock slope mapping (Riquelme et al., 2017), river bed topography (Rusnák et al., 2018) and volcanology (Gomez and Kennedy, 2018).

From the previous studies, SfM photogrammetry can render a promising quality and accuracy of outputs. However, the accuracy of the resulting 3D coordinates of features on the ground is controlled by the choice of the resolutions of the camera, focal length of the lens, image overlapping ratio, flying altitude, usage of ground control points (GCP) and the coordinates data collected from GNSS instrument to geo-reference the images. Mesas-Carrascosa et al. (2016) discovered that higher image overlapping ratio will render lower RMSE errors. However, extremely high image
overlapping ratio will produce large image datasets, causing longer processing time. It is often helpful to avoid collection of too many photos as it is difficult to process and store (Tannant, 2015). Therefore, optimum images overlapping ratio is set based on the site mapping condition. In this study, DJI Phantom 4 Pro, a brand new UAV mounted with a 20 megapixel camera is used to study the effect of flying height to the RMSE errors as well as the bundle adjustment of images with the usage of GCP and without GCP.

2.3 Real Time Kinematic (RTK)

Real Time Kinematic (RTK) is a technique used to receive GNSS signals at a stationary reference with known position coordinates and to use these to correct position data at a roving receiver in another location which increases the accuracy of signal received as depicted in Figure 2.2. Real Time Kinematic has become a popular high precision technique in Malaysia. The Malaysian Real-Time Kinematic Network (MyRTKnet) has been developed to facilitate RTK positioning in Malaysia. MyRTKnet consists 78 reference stations located at Peninsular Malaysia, Sabah and Sarawak (Jamil et al., 2010). Virtual Reference System (VRS) is one of the services provided by MyRTKnet. It is an integrated system which links and utilizes data from permanent reference stations to model errors throughout the coverage area. This model is used to synthesize virtual reference stations near the user’s location which then provide a localized set of standard format correction messages to the roving receiver (Department of Survey and Mapping Malaysia, 2005).
2.3.1 Accuracy of Real Time Kinematic (RTK)

The design accuracy of the minimum performance anticipated from MyRTKnet real-time services is outlined in Table 2.2. It would be evident from the table that centimeter level accuracy would be achievable where Virtual Reference System (VRS) services are available. Additionally, such level of accuracy could also be achieved within 30 km off MyRTKnet reference stations.

Table 2.2: Design accuracy of RTK (Department of Survey and Mapping Malaysia, 2005).

<table>
<thead>
<tr>
<th>Operation Mode (Instrumentation)</th>
<th>Design Real-Time Accuracy @ 95% Confidence Level (single-point positioning mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>VRS</td>
<td>4 cm</td>
</tr>
<tr>
<td>Single Base</td>
<td>4 cm</td>
</tr>
<tr>
<td>Network DGPS</td>
<td>0.3 m</td>
</tr>
</tbody>
</table>
A study on practical accuracy of the RTK positioning using VRS generated by MyRTKnet outside the network was conducted by Sulaiman et al. (2009). A conclusion can be made that the accuracy achieved was up to 6cm in horizontal component and up to 8cm in vertical component although the distance of data acquisition was 30km away from the nearest physical reference station. Similar research was conducted and the results show that the accuracies in the horizontal and height component were less than 1 cm and 9 cm respectively. It also shows that for areas within 30 km from the network, the accuracies obtained were within the said levels (Jamil et al., 2010). Saghravani and Saghravani (2009) discovered the vertical accuracy achieved by RTK-GPS is within 10cm. The overall reliability of RTK-GPS in case of elevation is more than 95%.

2.3.1.1 Factors Affecting Accuracy of Data Received from RTK

The accuracy of the data acquisition is not solely depended on the VRS network provided by the MyRTKnet. The overall performance will be dependent on uninterrupted data communication and GPS system characteristics, including data transmission latency, ionospheric activity, tropospheric activity, satellite geometry, baseline length, multipath effects and user instrumentation. Multipath error is a positioning error resulting from interference between radio waves which have travelled between the transmitter and the receiver by two paths of different electrical lengths. Data latency is the time taken for the user to send his approximate position to the GPS net server and receive back correction in order to initialize positioning. As tested by Department of Survey and Mapping Malaysia (2005), the average initialization time was 20 seconds. The common factors affecting time to initialize are rover station satellites geometry and sky clearance. Different RTK-GNSS instrument will render different quality of results based on its specifications and settings. The baseline
precision of a differential code solution for static and kinematic surveys is 40 cm (Leica Geosystems, 2012). This indicates that the instrument used must be compatible to receive a high accuracy data so that data less than 10cm error can be obtained. For higher accuracies, users may opt for post-processing approach, by obtaining the MyRTKnet data files in Receiver Independent Exchange format (RINEX format) which are stored and managed separately by Geodesy Section of JUPEM (Department of Survey and Mapping Malaysia, 2005). However, the time taken for this static method is longer compared to RTK.

2.4 Extraction of Discontinuity

The description of geological structures from rock exposures is traditionally achieved using a compass, an inclinometer, and a measuring tape. The data are recorded on a notebook and the rock faces are then photographed with a camera for documentation purposes. However, this method, known as the scanline mapping method, has several drawbacks. It cannot be applied to physically inaccessible or unsafe areas and unsupported underground mining areas. Most often, the rock mass exposures have either limited accessibility or complete inaccessibility, thus making field investigations time consuming, expensive, and hazardous. Furthermore, it only provides a linear sampling of a two-dimensional domain, resulting in important biases in the collected datasets. The ability of overcoming bias as well as the amount of data collected will have an effect on the discontinuity spacing and trace length measurements (Priest and Hudson, 1981). Planes in the rock outcrops depict a lot of useful information such as tectonic history, rock mass strength, sediment processes, etc. Hence, surface mapping techniques such as photogrammetry which can produce dense point clouds can overcome these practical difficulties as it can record the entire
discontinuities of the rock slope. Nevertheless, with the dense cloud, algorithm must be invented to extract the planes and discontinuities quantitatively so that it is useful for geotechnical designing work. A study was conducted to identify the discontinuity sets semi-automatically with Discontinuity Set Extractor (DSE) software and calculate the spacing of the sets (Buyer and Schubert, 2017). Also, a number of researchers have developed their own algorithms in different environments to extract the discontinuity. (Buyer and Schubert, 2016; Chen et al., 2016; Chen et al., 2017; Guo et al., 2017; Lato and Völge, 2012; Riquelme et al., 2014). However, the algorithm process is complicated and can hardly obtain. Dewez et al. (2016) created an automated geological plane extraction plugin named FACETS that is dedicated within CloudCompare software by applying least square fitting algorithm. The procedures are friendly user and can export quantitative discontinuity orientation (dip/dip direction). The case study has proven that the FACETS plugin can extract the geological planes accurately within 10° of difference compared to scanline survey method. However, only one research was done using the plugin. Thus, the plugin is used to extract the discontinuity of the rock mass in this research work and will be verified by the manual scanline survey method. The technique used allows for systematic mapping and the building of a permanent and huge database for rock mass characterization.

2.5 Generalised Hoek Brown Failure Criterion

The Hoek–Brown failure criterion (Hoek and Brown, 1980) is an empirical stress surface that is used in rock mechanics to predict the failure of rock. The Hoek–Brown failure criterion is an empirically derived relationship used to describe a non-linear increase in peak strength of isotropic rock with increasing confining stress. Hoek–Brown follows a non-linear, parabolic form that distinguishes it from the linear
Mohr–Coulomb failure criterion. The criterion includes companion procedures developed to provide a practical means to estimate rock mass strength from laboratory test values and field observations.

At first, the criterion was introduced in an attempt to provide input data for the analyses required for the design of underground excavations in hard rock. However, due to the lack of suitable alternatives, the criterion was soon adopted by the rock mechanics community and its use quickly spread beyond the original limits used in deriving the strength reduction relationships. Consequently, it has to be examined and improved from time to time to account for the wide range of practical problems to which the criterion was being applied. Generalised Hoek Brown Failure Criterion was introduced (Hoek et al., 2002). Since most geotechnical software is still written in terms of the Mohr-Coulomb failure criterion, it is necessary to determine equivalent angles of friction and cohesive strengths for each rock mass and stress. The relationship between major and minor principal stresses of Generalised Hoek-Brown and equivalent Mohr-Coulomb criteria is discovered. The significant contribution to this criterion was that it linked the equation to geological observations, initially to Bieniawski Rock Mass Rating and later to the Geological Strength Index (GSI) (Hoek and Brown, 1997). Besides, the disturbance factor was added to become a factor in determining the strength of the rock mass. The level of disturbance can be particularly significant when the slope is formed using blasting techniques. A rigorous set of analyses have been performed where the level of disturbance is considered as constant or linearly varying throughout the slope. The disturbance factor was found to have significant influence on the rock slope stability assessment, especially for poorer quality rock masses (Li et al., 2011). In addition, utilising stability charts to estimate the stability of cut rock slopes without considering the rock mass disturbance may lead to significant overestimations.
(Li and Wu, 2013) states that with the increase of D, the FoS of slope decreases linearly; as GSI increases, FoS increases non-linearly. When $\sigma_{ci}$ is small, FoS and $\sigma_{ci}$ shows certain nonlinear characteristic, when $\sigma_{ci}$ is large, they show linear relationship characteristics. As $m_i$ increases, FoS decreases first and then increases. Mohammadi and Tavakoli (2015) have investigated the applicability of generalized Hoek-Brown and Mohr-Coulomb failure criteria for determining the stresses on failure plane of rock. Results show that the obtained stresses and angles of failure plane for GHB results are closer to the empirical results. Moreover, the failure criterion is applied by Dong-ping et al. (2016) and Pan et al. (2017).

2.6 Kinematic Analysis

Kinematics refers to the motion of bodies without reference to the forces that cause them to move. Many rock cuts are stable on steep slopes even though they contain steeply inclined planes of weakness with exceedingly low strength; this happens when there is no freedom for a block to move along the weak surface because other ledges of intact rock are in the way. Should the blockage be removed by erosion, excavation, or growth of cracks, the slope would fail immediately Kinematic analysis is often used to investigate and determine the probability of structurally controlled failures such as planar sliding, wedge sliding, and toppling (Goodman, 1989). For rock slopes containing discontinuities, the uncertainty and variability in rock slope, generally arises from dominating joints and slope face azimuth and the discontinuity strength. Kinematic analysis is analysed mainly using the directionality of the discontinuous rock mass. The discontinuity orientations of the rock slope are projected onto a stereonet for the analysis. Case studies of rock slopes have been conducted by the researchers using kinematic analysis (Goh et al., 2017; Greif and Vlcko, 2017; Margottini et al., 2017;
Qin et al., 2017; Yoon et al., 2002; Zhou et al., 2017). Modes of failures of the rock slope (planar sliding, wedge sliding and flexural toppling) can be identified with its dip/dip direction that contributes to the failure.

2.7 Limit Equilibrium Method (LEM)

Limit Equilibrium Method (LEM) is the most common slope analysis method as it is a relative simple and quick analysis. The data required for analysis can easily be collected from the field (Tang et al., 2017). It is a method based on the assumptions about the slide surface. All points along the slip surface are on verge of failure. LEM will compute Factor of Safety (FoS) where it is a comparison ratio between resisting force and driving force. FoS which is less than one indicates the rock slope is unsafe and failure might occur anytime. Contrarily, FoS which is more than one indicates that the rock slope is safe.

Limit equilibrium method (LEM) is a powerful numerical tool for solving many problems of engineering and mathematical physics. Several limit equilibrium methods (LEM) have been developed for slope stability analysis. Fellenius (1936) introduced the first method, referred to as the Ordinary or the Swedish method, for a circular slip surface. Bishop (1955) advanced the first method introducing a new relationship for the base normal force. The equation for the FoS hence becomes non-linear. At the same time, Janbu N. (1954) developed a simplified method for non-circular failure surfaces, dividing a potential mass into several vertical slices and improved it in Janbu (1973). Later, Morgenstern-Price (1965), Spencer (1967), Sarma (1973) and several others made future contributions with different assumptions for the inter-slice forces. All LEM is based on certain assumptions for the inter-slice normal and shear forces. The comparisons between the methods of slices are presented in Table 2.3.
Assumptions made in limit equilibrium methods may possibly lead to over simplification. As a result, the results may not be realistic. However, over the years these methods have provided satisfactory results for engineering applications. To have more realistic results on slope stability condition this method can further be integrated with probabilistic methods that can help to recognize and assess uncertainties among the governing parameters in a systematic manner (Alzo’ubi, 2016). Kainthola et al. (2013) used Bishop LEM to conduct probabilistic and sensitivity analysis on the two hill slopes, Chandaak and Chhera in India due to the variability of the parameters of the hills. Besides, locating the critical failure surface of heterogeneous rock slopes is one of the problems which optimization algorithms serve very well to solve them. Bolton et al. (2003) used global optimization algorithm with Janbu’s simplified method and Spencer’s method to determine the critical failure surface in the slope stability analysis due to the rock having layered profile where the slip surface is complex. No assumptions are required with regards to the geometry of the failure surface and no restrictions are placed on the positions of the initiation and termination point. For homogeneous soils, the assumed failure surface is often of a regular shape and the method of vertical slices in which assumptions about the geometry of the failure surface are made is not suitable. As a result the solution is rendered effectively.
Agam et al. (2016) studied the sensitivity analysis of a natural-unreinforced slope in Kepong, Kuala Lumpur. Under Mohr-Coulomb failure criterion, Spencer's and General Limit Equilibrium methods of slices were used in the analysis to determine the influence of varying parameters values towards the change in FoS. In the analysis, water table location has the highest influence to the change in FoS of the slope, followed by friction angle, cohesion and unit weight. However, this condition only applies to the earth layer at which the critical slip surface is passing. For the earth layer where the critical slip surface does not pass, the parameters have insignificant influence towards the change in FoS. In addition, the differences in safety factor obtained by Spencer’s and General Limit Equilibrium methods are very nominal and showed a good agreement to each other.

2.7.1 Morgenstern-Price Analysis Method

Morgenstern Price method is used for calculation of the safety factor (Morgenstern and Price, 1965). The method is one of the popular methods among limit equilibrium methods. In this method, both moment and force equilibrium (horizontal and vertical) will be satisfied simultaneously for any shape of failure surfaces. It assumes an inter-slice force function \( f(x) \). It is more well-mannered than other computational algorithms in the slope stability field. The essence of the method is to divide the sliding mass into a finite number of vertical slices. The method assumes the inclination of the resultant inter-slice force varying symmetrically across the slide mass. Khajehzadeh et al. (2011) utilized the algorithm of Morgenstern Price method to calculate the FoS of the general slip surfaces. The general slip surfaces of the slope were identified using a newly developed heuristic global optimization algorithm, called gravitational search algorithm (GSA).
2.7.2 Cuckoo Search Slip Surface Search Method

Cuckoo Search (CS) is a meta-heuristic search method that is formulated by Yang and Deb (2009). The proposed algorithm has been validated and compared with other algorithms such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO). From simulations and comparisons, it is discovered that CS is superior to PSO and GA algorithms as it is much more efficient in finding the global optima with higher success rates. Besides, the computing time of CS is much shorter than GA and PSO. This might be due to the fine balance of randomization and intensification of CS, and less number of control parameters. In fact, there are only two parameters in CS algorithm: population size $n$ and $p_a$. CS is more generic and robust for many optimization problems, comparing with other meta-heuristic algorithms. The advantages of CS were also highlighted by Wu (2012) and Rocscience (2016) during the application in rock slope stability analysis. CS is able to locate absolute global minimum failure surface more effectively and efficiently (about three times faster) than Simulated Annealing. When combined with Local Monte Carlo (LCM) for further optimization of the critical failure surface, a refined surface with the lowest factor of safety of a slope geometry can be found. Cuckoo Search is also able to display the various failure modes found during the search as well. The review on Cuckoo Search method was conducted by Mohamad et al. (2014). Conclusion is made that CS outperforms other evolutionary algorithms from the benchmark tests such as GA, PSO, Tabu Search and artificial bee colony (ABC) during the benchmark tests. Therefore, cuckoo search is applied in the study for locating the global minimum slip surface of the rock slope due to its effectiveness and efficiency. Moreover, it is a stochastic method which is more suitable for rock slope which consists of irregular and heterogeneous anisotropic plane and material which will cause non-circular slip surface.
2.7.3 Probabilistic Method

Uncertainty and variability are inevitable in engineering geology studies dealing with natural materials. This prevails because rocks and soils are inherently heterogeneous, insufficient amount of information for site conditions are available and the understanding of failure mechanisms is incomplete. Besides, rock slope stability is highly dependent on discontinuity characteristics and it is unpredictable (Hoek, 2007). Hence, to overcome this limitation, the probabilistic analysis method is proposed. Random properties for geometric and strength parameters of discontinuities play a critical role in the probabilistic analysis. Probabilistic analysis has been used as an effective approach to evaluate uncertainty. Probabilistic analysis of rock slope stability using Monte Carlo Simulation was studied and comparisons with deterministic approach were conducted (Mat et al., 2014; Park and West, 2001; Park et al., 2005). The researchers conclude that the probabilistic method yields significantly different results from those of the deterministic analysis. In some cases, the deterministic analysis did not indicate the slope failure condition as it is based on the fixed value of discontinuity and rock parameters. In reality, it is having a spatial variability in the rock mass properties and the rock slope stability should be analysed according to the spatial distribution in probabilistic method. FoS is the outcome obtained from the rock slope stability analysis. It 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 is more suitable as it will provide FoS as random variables with probability distribution (Raghuvanshi, 2017). (Zhao et al., 2016) carry out probabilistic analysis using Monte-Carlo simulation method for the rock block evaluation where plane roughness, friction angle, and cohesion were considered.
as random variables. The results of the research showed that the probabilistic model can be used as a basis for evaluating the reliability of the block. (Tao et al., 2014) conducted probabilistic slope stability analysis Using Morgenstern-Price Method. They found out that the failure probability increased with the increasing of slope angle, slope height and the coefficient of variability and conclude that the combined use of factor of safety and failure probability could be effective enough for the slope safety evaluation. In short, probabilistic method which considers the variability of the characteristics of the rock mass should be used for rock slope stability analysis.
CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter explains the execution of the research work and methods used in detailed. The study was conducted at two locations, a slope in the main campus of Universiti Sains Malaysia (USM) and a rock slope excavated for Project Lencongan Banjir Barat Timah Tasoh, Perlis located at Kampung Wai, Perlis.

The slope in USM Main Campus was studied to determine the accuracy of the photogrammetric data processed with and without GCP at different flying heights. Two phases of methodology was conducted: (i) fieldwork data acquisition and (ii) processing of digital photographs and datasets. Aerial images of the slope were taken at three different flying heights, at 50m, 70m and 80m, by using UAV. 10 GCP were distributed evenly on the mapping area at different elevations of the slope using GCP mat and spray. The coordinates of the GCP were measured using RTK-GNSS instrument. The images dataset captured at different flying heights were going through bundle adjustment with and without GCP respectively by using Agisoft Photoscan Professional software. The methodology for the slope study in USM Main Campus was stopped at Section 3.4, the processing of digital photographs and datasets.

For the rock slope excavated for Project Lencongan Banjir Barat Timah Tasoh, Perlis which is located at Kampung Wai, Perlis, the methodology conducted was based on six phases: (i) fieldwork data acquisition, (ii) processing of digital photographs and datasets, (iii) extraction of discontinuity data automatically, (iv) verification of discontinuity data obtained digitally and manually, (v) rock slope kinematic and sensitivity analysis and (vi) rock slope limit equilibrium analysis using deterministic
method in 3D and probabilistic method in 2D by applying Morgenstern-Price analysis method and Cuckoo Search as slip surface analysis method. In the fieldwork data acquisition, the slope terrain mapping using photogrammetry approach with GCP survey was conducted. Scanline survey was carried out as well to determine the discontinuity of the rock slope. The equipment used in the fieldwork data acquisition was UAV, GCP marker, RTK-GNSS, total station, geological compass and measuring tape. The software utilized in the processing the digital photographs and datasets with GCP was Agisoft Photoscan Professional. The outputs from the processes were dense point clouds, 3D textured model, orthophoto and DSM. The dense point clouds were imported into CloudCompare software to extract the geological planes or discontinuity pattern of the rock slope using FACET plugin. The discontinuity data extracted was verified with the data measured manually using scanline survey method. With the discontinuity data, Rocscience Dips software was used for analyzing the mean dip/dip direction of the rock slope. Kinematic and sensitivity analysis were also conducted to determine the critical percentage of failure of the various failure modes such as plane sliding, wedge sliding and flexural toppling. Generalised Hoek-Brown Failure Criterion was applied to the rock slope where the parameters were obtained from the Rocscience RocData software. UCS test was conducted to obtain the UCS value of the rock. To analyse the rock slope stability, 3D model geometry of the rock slope was imported into Rocscience Slide3 software to carry out 3D deterministic LEA. Then, the cross-section of the global minimum slip surface identified in 3D was extracted and imported into Rocscience Slide 2018 for deterministic and probabilistic LEA. Morgenstern-Price method was applied for LEA and Cuckoo Search as slip surface analysis method for both 3D and 2D analysis. The critical FoS of the rock slope will be obtained. The overall procedure is illustrated in Figure 3.1.
Figure 3.1: Flow chart of research methodology.
3.2 Study Area

Two study areas have been selected to conduct this research work: a slope in Main Campus of Universiti Sains Malaysia (USM), Gelugor, Penang and a rock slope in Kampung Wai, Kuala Perlis, Perlis which was excavated for Projek Lencongan Banjir Barat Timah Tasoh, Perlis. A slope in USM Main Campus was selected to determine the accuracy of the photogrammetric data processed with GCP and without GCP because it is a gentle slope where the accessibility is possible. The site environment is suitable to carry out the accuracy assessment of the photogrammetric data processed with and without GCP. Then, the results obtained from the accuracy assessment were applied in the fieldwork data acquisition of the rock slope in Perlis.

3.2.1 Slope in USM Main Campus

Universiti Sains Malaysia (USM) Main Campus is located in Gelugor, Penang, the Northern region of Peninsular Malaysia. The slope as shown in Figure 3.2 is located near to the USM main gate with latitude of 5.361812 and longitude of 100.308297 as depicted in Figure 3.3.

Figure 3.2: Slope in USM Main Campus.
3.2.2 Rock Slope in Perlis

The rock slope which was excavated for Projek Lencongan Banjir Barat Timah Tasoh as displayed in Figure 3.4 is situated at Kampung Wai, Kuala Perlis, Perlis where it is located at the Northwest of Peninsular Malaysia. The rock slope which is made up of limestone was excavated to channel the water from Timah Tasoh Dam to the sea. The exact location of the rock slope is at latitude of 6.428794 and longitude of 100.143884 as illustrated in Figure 3.5.

Figure 3.3: Location of the slope in USM Main Campus (latitude, longitude: 5.361812, 100.308297) (Google Map) [2nd February 2018].

Figure 3.4: Rock slope in Perlis.
3.2.2.1 Geological Background

The topography of Northwest Peninsular Malaysia is mostly flat coastal plain. The geology of Northwest Peninsular Malaysia is dominated by four major stratigraphic divisions: Machinchang Formation, Setul Group; Kubang Pasu and Singa Formations, and Chuping Limestone. There are also several minor stratigraphic divisions: Bukit China Granite and Bukit Arang Beds as presented in Figure 3.6. Among all, the most impressive is the Setul Boundary range, composed of Palaeozoic limestone, which is a steep, continuous mountain range with peaks reaching 553 m high and forming a natural border between West Perlis and Thailand. An almost complete Palaeozoic sedimentary succession is preserved, from the Cambrian to the Permian. On the mainland, Ordovician to Permian strata forms a roughly North-South trending fold belt. More specifically in Perlis, the stratigraphic succession generally young eastwards starting from the Setul Boundary Range, but repeats itself in the opposite direction east of the Chuping Hills, which forms the axis of a broad syncline (Jones, 1981).
Exposures of carbonates are mainly in the form of steep karst hills and towers, which can either be isolated or form part of long ranges. Exposures of clastic strata commonly crop out of the flat coastal plain as small hills or ridges. The outcropping stratum of the study area is limestone as presented in Figure 3.7. It falls under the Setul Group. 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.

Figure 3.6: Geological map (stratigraphy) of Perlis and north of Kedah (Jones, 1981).
3.3 Slope Mapping – Fieldwork Data Acquisition

UAV with a mounted camera is used for slope mapping by taking aerial or side images of the slope based on the purpose of the project. All the images are 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 is set up on the study area to measure the exact coordinates of the location using RTK-GNSS instrument in which the coordinates are auto-corrected by the nearest RTK base station.

3.3.1 Design, Components and Specifications of UAV

UAV, known as a drone, is an aircraft without a human pilot aboard. It is a component of an unmanned aircraft system (UAS), including an aircraft, ground-based controller and a system of communications between them. DJI Phantom 4 Pro, a quadcopter as displayed in Figure 3.8 was used in this study. It consists of four rotors with two pairs of identical fixed pitched propellers which help to lift the aircraft; two clockwise and two anticlockwise. It comes with a built-in high quality camera which is the most important component when high precision and accuracy output is needed. To ensure the images captured are clear and stable, the camera is attached to the 3-axis gimbal which is a steady platform provider. It controls the pitch, roll and yaw angles of the camera. Aircraft body, battery, infrared sensing system, forward, rear and downward vision system, gimbal and GPS receiver are the main components of the UAV. Some important specifications of DJI Phantom 4 Pro are outlined in Table 3.1.

![Figure 3.8: DJI Phantom 4 Pro Aircraft (DJI Phantom 4 Pro, 2016).](image)
Table 3.1: Specification of DJI Phantom 4 Pro (DJI Phantom 4 Pro, 2016).

<table>
<thead>
<tr>
<th>Aircraft</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (Inclusive of Battery and Propellers)</td>
<td>1388g</td>
</tr>
<tr>
<td>Diagonal Size (Propellers Excluded)</td>
<td>350mm</td>
</tr>
<tr>
<td>Max Ascent Speed</td>
<td>P-mode: 5m/s ; S-mode: 6m/s</td>
</tr>
<tr>
<td>Max Descent Speed</td>
<td>P-mode: 3m/s ; S-mode: 4m/s</td>
</tr>
<tr>
<td>Max Speed</td>
<td>P-mode: 14m/s ; S-mode: 20m/s ; A-mode: 16m/s</td>
</tr>
<tr>
<td>Max Tilt Angle</td>
<td>P-mode: 25° ; S-mode:42° ; A-mode: 35°</td>
</tr>
<tr>
<td>Max Service Ceiling Above Sea Level</td>
<td>19685 feet (6000m)</td>
</tr>
<tr>
<td>Max Wind Speed Resistance</td>
<td>10m/s</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>0°C to 40°C</td>
</tr>
<tr>
<td>Satellite Positioning Systems</td>
<td>GPS / GLONASS</td>
</tr>
<tr>
<td>Hover Accuracy Range (Vertical)</td>
<td>±0.1 m (with Vision Positioning) ±0.5 m (with GPS Positioning)</td>
</tr>
<tr>
<td>Hover Accuracy Range (Horizontal)</td>
<td>±0.3 m (with Vision Positioning) ±1.5 m (with GPS Positioning)</td>
</tr>
</tbody>
</table>

| Camera                              |          |
| Sensor                              | 1” CMOS  |
|                                     | Effective pixels: 20M |
| Lens                                | FOV 84° 8.8 mm/24 mm (35 mm format equivalent) f/2.8 - f/11 auto focus at 1 m - ∞ |
| ISO Range (Video)                   | 100 - 3200 (Auto) ; 100 - 6400 (Manual) |
| ISO Range (Photo)                   | 100 - 3200 (Auto) ; 100- 12800 (Manual) |
| Mechanical Shutter Speed            | 8 - 1/2000 s |
| Electronic Shutter Speed            | 8 - 1/8000 s |
| Image Size                          | 3:2 Aspect Ratio: 5472 × 3648 |
|                                     | 4:3 Aspect Ratio: 4864 × 3648 |
|                                     | 16:9 Aspect Ratio: 5472 × 3078 |
| Photo                               | JPEG, DNG (RAW), JPEG + DNG |
| Video                               | MP4/MOV (AVC/H.264; HEVC/H.265) |
| Supported SD Cards                  | Micro SD |
|                                     | Max Capacity: 128GB |
|                                     | Write speed ≥15MB/s, Class 10 or UHS-1 rating required |

| Gimbal                              |          |
| Stabilization                       | 3-axis (pitch, roll, yaw) |
| Controllable Range                  | Pitch: -90° to +30° |
| Max Controllable Angular Speed      | Pitch: 90°/s |
| Angular Control Accuracy            | ±0.02° |
3.3.2 Ground Control Point (GCP)

Before commencing any operations on collecting data via UAV, a detailed site study has to be carried out to determine the size and the condition of the area of interest. The study is important for ground control points (GCPs) set up in the study area as it will have effects on the photos alignment later in the processing of photogrammetric dataset. GCPs need to be distributed evenly at each corner of the study area as well as at any significant difference of ground elevations. GCPs are physically marked locations, also known as markers, with a fixed position and their coordinates are determined. 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. RTK base stations are available throughout Malaysia as shown in Figure 3.9. The status and availability of the nearest base station to the site must be checked and ensured to be in good quality so that the coordinate data received and corrected is accurate and reliable. Total Station can be used to determine the coordinates as well if there is a known benchmark near to the study area. However, RTK-GNSS instrument as shown in Figure 3.10 is a better and reliable tool to obtain the coordinates compared to total station since it will render the data of the coordinates instantaneously with corrections being done in it and the data collection can be conducted anywhere within 30km from the base station. The guidelines of data acquisition using Virtual Reference System (VRS) in RTK are shown in Table 3.2. The usage of total station is tedious and problematic if the benchmark is too far away and the study area is huge with steep slopes and elevations. The accuracy of the data obtained via total station might be affected as well. The application of GCPs can increase the accuracy of the bundle adjustment of the dataset. The coordinates obtained via RTK-GNSS in X, Y and Z axes, also known as latitude, longitude and
altitude respectively, can geo-reference all the images captured and hence produce photogrammetric data with high global and local accuracy. Surveying work using RTK-GNSS instrument and total station is shown in Figure 3.11. The flowchart of utilizing the RTK-GNSS instrument is outlined in Figure 3.12.

![Figure 3.9: Location of RTK base stations in Malaysia. (MyRTKnet, 2018)](image)

Table 3.2: Guidelines for Data Acquisition Using MyRTKnet (Department of Survey and Mapping Malaysia, 2005).

<table>
<thead>
<tr>
<th>Item</th>
<th>VRS</th>
<th>Single Base</th>
<th>Network Base DGPS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Network Coverage</strong></td>
<td>Within dense network or max. 30 km outside the dense network.</td>
<td>Within 30 km of the single base reference station</td>
<td>Whole of Peninsular Malaysia or within 150 km of Kota Kinabalu &amp; Kuching</td>
</tr>
<tr>
<td><strong>Observation Sessions</strong></td>
<td>Static mode with observation epoch of five (5) seconds of 10 epochs.</td>
<td>Static mode with observation epoch of five (5) seconds of 10 epochs.</td>
<td>Static mode with observation epoch of five (5) seconds of 10 epochs.</td>
</tr>
<tr>
<td><strong>Satellite Geometry</strong></td>
<td>Min. 5 satellites in view for the entire session.</td>
<td>Min. 5 satellites in view for the entire session.</td>
<td>Min. 4 satellites in view for the entire session.</td>
</tr>
<tr>
<td><strong>Sky Coverage</strong></td>
<td>At least 90%, with telescopic antenna poles of up to 10 m being allowed.</td>
<td>At least 90%, with telescopic antenna poles of up to 10 m being allowed.</td>
<td>At least 90%, with telescopic antenna poles of up to 10 m being allowed.</td>
</tr>
</tbody>
</table>
Figure 3.10: RTK-GNSS Instrument - Leica Viva UNO CS10 controller with AS05 antenna set up on a GCP marker at Slope in USM.

Figure 3.11: Surveying at rock slope in Perlis (a) RTK-GNSS, (b) Total Station.

Figure 3.12: Flowchart of measuring coordinates of GCP by RTK-GNSS instrument.
3.3.3 Flight Path Planning and Photogrammetric Acquisition

After GCPs were marked on the study area, the next step is to capture images of the study area. However, planning has to be done before commencing any operations on collecting data. Observing any obstacles or hazards near to the study area as well as the wind speed is important to ensure the UAV can be controlled in a safe manner. Then, UAV components such as propellers and battery were fixed to the aircraft and the motors and sensors were checked to ensure they were in good condition. Next, the controller and UAV were switched on. GNSS signal must be strong, with connection to more than 10 satellites, to fly the mission. Select 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. 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, showing the global position, distance covered, flying height above ground, number of images will be captured, the estimated battery usage and duration of the flying mission. Table 3.4 shows the details of one of the flight missions at the slope in USM. Its flight pathway is shown in Figure 3.13. On the other hand, the details of the flight mission at the rock slope in Perlis with its flight pathway at different course angles are shown in Table 3.4 and Figure 3.14 respectively.

Table 3.3: Details of flight mission at the slope in USM.

<table>
<thead>
<tr>
<th>Details of Flight Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date and time</td>
</tr>
<tr>
<td>Area covered</td>
</tr>
<tr>
<td>Distance covered</td>
</tr>
<tr>
<td>Altitude</td>
</tr>
<tr>
<td>Front Overlap Ratio</td>
</tr>
<tr>
<td>Side Overlap Ratio</td>
</tr>
<tr>
<td>Resolution</td>
</tr>
</tbody>
</table>
Figure 3.13: Flight pathway for slope data acquisition in USM using UAV.

Table 3.4: Details of flight mission at the rock slope in Perlis.

<table>
<thead>
<tr>
<th>Details of Flight Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date and time</td>
</tr>
<tr>
<td>Area covered</td>
</tr>
<tr>
<td>Distance covered</td>
</tr>
<tr>
<td>Altitude</td>
</tr>
<tr>
<td>Front Overlap Ratio</td>
</tr>
<tr>
<td>Side Overlap Ratio</td>
</tr>
<tr>
<td>Resolution</td>
</tr>
</tbody>
</table>

Figure 3.14: Flight pathway for rock slope data acquisition using UAV at (a) course angle 0\(^\circ\), (b) course angle 90\(^\circ\).
After take-off, the UAV will follow its pre-set tasks autonomously until completion. UAV will capture photo at each waypoint. In an unexpected event where the connection is lost, the aircraft can be controlled manually. When the last waypoint was reached, the UAV will return to its take-off location by switching to the “return to home” mode. The landing can be performed either manually or automatically. If the size of the survey area were too large and the capacity of one battery were inadequate for one flight, additional flights can be performed by replacing with a new battery and the data collection can be continued from where it stops. The data can be combined easily.

3.4 Processing of Digital Photographs and Dataset

Photogrammetric data processing is needed to generate a geo-referenced 3D point cloud from the unordered, overlapping and airborne image collection of the surface. In this study, Agisoft Photoscan Professional software was used to process the geo-tagged images obtained from the UAV. At first, the geo-tagged photographs were imported into the software and followed by photo alignment in which the accuracy was set to high with the pair pre-selection based on image GNSS coordinates as stored in the Joint Photographic Experts Group Exchangeable Image File Format (JPEG-EXIF) headers. The structure from motion (SfM) algorithms in the software will extract and match the same features appeared in the images automatically known as tie points and followed by bundle block adjustment. Sparse clouds will be produced as an output of the process. Next, the markers were placed on each images accurately and precisely based on the number of the markers followed by inputting the coordinates of each marker (GCP). The tie points in each image were realigned based on the coordinates of the GCPs. Then, dense geometry was ready to be constructed with its accuracy set to
high level to obtain a denser point clouds. Construction of 3D textured model, Digital Surface Model (DSM) and orthophoto were then processed from the dense point clouds.

A summary of the procedure is presented in Figure 3.15.

![Flowchart of processing images in Agisoft Photoscan Professional.](image)

**Figure 3.15:** Flowchart of processing images in Agisoft Photoscan Professional.

### 3.5 Extraction of Elevation Data

Digital Surface Model (DSM) generated from high accuracy dense point cloud was exported from Agisoft Photoscan Professional software in .tiff format and imported into Global Mapper Software. Then, draw a line on the DSM using 3D path profile. A cross-section profile will be shown with an interactive query function where it will show the elevation and coordinates of the point following the movement of the cursor of the mouse. An alternative way is to input the known coordinates of the beginning and the end of the line. Same cross-section can be shown as well. The elevation and coordinates data can be exported in Comma Separated Values (CSV) file format to obtain the values of the data. The procedure is summarised in Figure 3.16.

![Flowchart of extracting coordinates using Global Mapper software.](image)

**Figure 3.16:** Flowchart of extracting coordinates using Global Mapper software.
3.6 **Rock Slope Discontinuity Orientation Acquisition**

Discontinuity is a plane or surface that indicates a change in physical or chemical characteristics in a rock mass. It can be a bedding plane, joint, fracture or fault plane. In this study, orientation of the bedding plane was measured using scanline survey method. The discontinuity orientation or dip / dip direction of the rock slope were measured along a reference line at 1.70m above the ground level which was reachable. Geological compass as appeared in Figure 3.17, clinometer and measuring tapes are the tools used for the dip / dip direction measurement. The sampling was taken randomly along the lines.

![Geological compass](image)

**Figure 3.17:** Geological compass.

3.7 **Extraction of Geological Planes**

The high accuracy dense point cloud generated based on GCP was imported into the open-source software, CloudCompare, using the FACET plugin to extract the geological planes in the rock outcrop. There are two methods of extracting the discontinuities: kd-tree (KD) approach and Fast Marching (FM) approach with both methods implementing a least square fitting algorithm. Kd-tree approach divides the 3D point cloud recursively into small planar patches until the points fit the best-fitting plane given the Root Mean Square (RMS) threshold. These planar patches are then
back clustered into bigger facets according to a co-planarity criterion. On the other hand, FM approach divides the 3D point cloud systematically into smaller patches and subsequently regroups them. Hence, all the patches will have similar size. After the meshes or facets are extracted, they can be classified by orientation (dip/dip direction) into single planes and plane families. A stereogram can be produced which is useful for rock slope stability analysis. Query can be done on the stereogram with the outcrop portion being selected. Lastly, the facets data can be exported as Comma-Separated-Variable (CSV) ASCII file or shapefiles for further analysis in other software (Dewez et al., 2016). Figure 3.18 depicts the summary of the methodology of using facet plugin in CloudCompare to extract geological planes from 3D point clouds.

Figure 3.18: Flowchart of extraction of geological planes in CloudCompare using FACET plugin.
3.8 **Rock Mass Properties**

Data input on rock mass properties is very important for rock slope stability analysis either using limit equilibrium method or finite element model. Without the reliable geotechnical input parameters, the analysis carried out will not be useful. In this study, generalized Hoek-Brown failure criterion was utilized to study the rock slope. It is an empirical failure criterion which establishes the strength of rock in terms of major and minor principal stresses. It predicts strength envelopes that agree well with values determined from laboratory triaxial tests of intact rock and from observed failures in jointed rock masses. Uniaxial Compressive Test was conducted to determine the uniaxial compressive strength (UCS) of the rock. For other geotechnical input parameters, Rocscience RocData was being used as it is a useful analysing tool in determining rock material properties. It enables users to easily visualize the effects of changes in input parameters on rock and soil failure envelopes.

3.8.1 **Uniaxial Compressive Strength (UCS) Test**

Uniaxial compressive test was carried out to determine the compressive strength of the rock, also known as uniaxial compressive strength (UCS). The test was conducted by following the standard methods by ASTM D7012-14, (2008) Method C. Rock samples with no visible open fractures, voids or other potential weak features were collected from the rock slope. The rock samples were cored using rock coring machine as shown in Figure 3.19a. Since, the rock specimen shall have a length to diameter ratio of 2.0 to 2.5 and the diameter shall be greater than 48 mm, the rock samples were cored using 50mm diameter coring head to obtain a 50mm diameter rock specimen as displayed in Figure 3.20. Then, the rock specimen was cut and trimmed to 100mm length by using rock cutter trimmer as illustrated in Figure 3.19b. The upper
and lower surface of the rock specimen must be smoothened to ensure the load can be applied uniformly. Next, the ready rock specimen was inserted into Universal Testing Machine (UTM) shown in Figure 3.21 for UCS testing. The compression pace rate was 0.5MPa per second. The peak load achieved by a rock specimen was divided by the area of the rock specimen to obtain the compressive strength.

![Figure 3.19](image1.png)  
(a) Rock coring machine, (b) Rock cutter trimmer.

![Figure 3.20](image2.png)  
Figure 3.20: Rock specimen with 50mm diameter and 100mm length.
3.8.2 Generalised Hoek-Brown Failure Criterion

The Hoek-Brown failure criterion is an empirically derived relationship used to describe a non-linear increase in peak strength of isotropic rock with increasing confining stress. Following the parabolic, non-linear form of Hoek-Brown discriminate it from the linear Mohr-Coulomb failure criterion. The criterion includes companion procedures established to provide a practical means to estimate rock mass strength from laboratory test values and field observations. Hoek-Brown assumes independence of the intermediate principal stress (Eberhardt, 2012). The main purpose of Hoek-Brown criterion is to estimate rock mass strength by scaling the relationship derived according to the present geological conditions. The criterion was conceived based on Hoek’s experiences with brittle rock failure and his use of a parabolic Mohr envelope to define the relationship between shear and normal stress at fracture initiation (Aksoy et al., 2016). Accordingly, the Hoek-Brown criterion is empirical with no fundamental relationship between the constants included in the criterion and any physical
characteristics of the rock (Hoek, 1983). The original non-linear Hoek-Brown failure criterion for intact rock was introduced in equation 3.1.

\[
\sigma_1' = \sigma_3' + \sigma_{ci} \left( m \frac{\sigma_3'}{\sigma_{ci}} + s \right)^{0.5}
\] (3.1)

where \(\sigma_1'\) and \(\sigma_3'\) are the major and minor principal stresses at failure, \(\sigma_{ci}\) is the uniaxial compressive strength of the intact rock, and \(m\) and \(s\) are dimensionless empirical material constants where \(s\) is equal to one for intact rock. As an empirical criterion, the Hoek-Brown criterion has been restuctured several times in response to experience gained with its usage. Moreover, certain practical limitations were addressed in these updates (Hoek and Brown, 1988). These updates primarily involve adjustments to improve the estimate of rock mass strength. Generalized Hoek-Brown criterion for jointed rock masses is introduced by Hoek (Hoek et al., 2002) in which the shape of the principal stress plot or the Mohr envelope could be adjusted by means of a variable coefficient \(a\) in place of the square root term in equation 3.1 as shown in equation 3.2.

\[
\sigma_1' = \sigma_3' + \sigma_{ci} \left( m_b \frac{\sigma_3'}{\sigma_{ci}} + s \right)^a
\] (3.2)

where \(m_b\) is a reduced value of the material constant \(m_i\) for the intact rock and is calculated by equation 3.3.

\[
m_b = m_i \exp \left( \frac{GSI - 100}{28 - 14D} \right)
\] (3.3)

\(s\) is a constant depending upon the characteristics of the rock mass as in equation 3.4.
Also, parameter $a$ is a constant for the rock mass given by equation 3.5.

$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right)$$  \hspace{1cm} (3.4)

$$a = \frac{1}{2} + \frac{1}{6}\left[e^{-\frac{6GSI}{15}} - e^{-\frac{2GSI}{3}}\right]$$  \hspace{1cm} (3.5)

An associated Windows program called Rocscience RocData has been developed to provide a convenient means of solving and plotting the equations. However, in the equation 3.3, 3.4 and 3.5, uniaxial compressive strength of intact rock ($\sigma_{ci}$), $m_i$ value, Geological Strength Index ($GSI$) and disturbance factor ($D$) are yet to be determined. They can be determined from a rock database in Rocscience RocData Version 5.0 software.

### 3.8.2.1 Uniaxial Compressive Strength of Intact Rock ($\sigma_{ci}$)

UCS is the ultimate compressive stress of the rock specimen failure under uniaxial compression conditions. The UCS value can be chosen based on the field estimate of strength and type of rock in Figure 3.22.
### Mi Value

Mi value is the material constant for the intact rock as shown in Figure 3.23. The value of mi depends on many factors, such as mineral composition, grain size, and cementation of rocks. Hoek and Brown (1997) suggested that the values of mi should be calculated over a range of confining stress $\sigma_3$ of from 0 to 0.5 $\sigma_{ci}$ by using regression methods and that at least five sets of triaxial tests should be included in the regression analysis. Given that the reliability of mi values calculated from regression analysis depends on the quantity and quality of test data used in the regression method. The latest version of the guidelines for determining mi values for different rock types that can be used for preliminary design when triaxial tests are not available was proposed by Hoek (2007) based on a more detailed lithology classification of rocks, and the range of mi values depended on the accuracy of the geologic description of rock types. Shen and

<table>
<thead>
<tr>
<th>Field Estimate of Strength</th>
<th>Examples</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen can only be chipped with a geological hammer</td>
<td>Fresh basalt, quartz, diabase, gneiss, granite, quartzite.</td>
<td>&gt;250</td>
</tr>
<tr>
<td>Specimen requires many blows of a geological hammer to fracture it</td>
<td>Anabasite, sandstone, basalt, gneiss, gneiss, granodiorite, limestone, marble, rhyolite, tuff.</td>
<td>100-250</td>
</tr>
<tr>
<td>Specimen requires more than one blow of a geological hammer to fracture it</td>
<td>Limestone, marble, phyllite, sandstone, schist, shale.</td>
<td>50-100</td>
</tr>
<tr>
<td>Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer</td>
<td>Claystone, coal, concrete, schist, shale, slatelane.</td>
<td>25-50</td>
</tr>
<tr>
<td>Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer</td>
<td>Chalk, rocksalt, petacl.</td>
<td>5-25</td>
</tr>
<tr>
<td>Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife</td>
<td>Highly weathered or altered rock.</td>
<td>1-5</td>
</tr>
<tr>
<td>Indented by thumbnail.</td>
<td>Stiff fault gouge.</td>
<td>0.25-1</td>
</tr>
</tbody>
</table>

Figure 3.22: Uniaxial Compressive Strength (UCS) of intact rock.
Karakus (2014) proposed a simplified method that can estimate mi values using information on rock types and the UCS of intact rocks.

![List of Mi Values](image)

Figure 3.23: Mi value of rock type.

### 3.8.2.3 Geological Strength Index (GSI)

Geological Strength Index (GSI) is a system of rock mass characterization that has been developed in engineering rock mechanics to meet the need for reliable input data related to rock mass properties required as input for numerical analysis or closed-form solutions for designing tunnels, slopes, or foundations in rocks. This index is based on an assessment of the lithology, structure, and condition of discontinuity surfaces in the rock mass, and it is estimated from visual examination of the rock mass exposed in outcrops. GSI resulted from combining observations of the rock mass conditions with the relationships developed from the experience gained using the RMR-system (Marinos et al., 2007). GSI relates the Hoek Brown failure criterion to geological observations in the field. The relationship between rock mass structure and rock discontinuity surface conditions is used to estimate an average GSI value represented in the form of diagonal contours as displayed in Figure 3.24.
3.8.2.4 Disturbance Factor (D)

Disturbance factor, $D$ depends upon the degree of disturbance to which the rock mass has been subjected by blast damage or stress relaxation. It varies from 0 for undisturbed in situ rock masses to 1 for very disturbed rock masses. Figure 3.25 shows the disturbance factor for the application in rock slope.

![Figure 3.25: Disturbance Factor (D).](image)
3.9 Rock Slope Kinematic Analysis

Kinematic analysis is a method used to analyze the various modes of potential rock slope failures such as planar sliding, wedge sliding and flexural toppling that occur due to the presence of unfavorable oriented discontinuities. Discontinuities are geologic breaks such as joints, faults, bedding planes, foliation, and shear zones that can potentially serve as failure planes. Different types of slope failure are associated with different geological structures and the structural patterns should be identified when examining pole plots in the stereonet as illustrated in Figure 3.26. Kinematic analysis is based on Markland's test as described by (Hoek and Bray, 1981). According to the Markland's test, a planar failure is likely to occur when a discontinuity dips in the same direction (within 20°) as the slope face, at an angle less than the slope angle but greater than the friction angle along the failure plane. A wedge failure may occur when the line of intersection of two discontinuities forming the wedge-shaped block plunges in the same direction as the slope face and the plunge angle is less than the slope angle but greater than the friction angle along the failure plane. A toppling failure may happen when a steeply dipping discontinuity is parallel to the slope face (within 30°) and dips into it (Yoon et al., 2002).

![Figure 3.26: Slope failures and its stereonet (a) Planar Sliding, (b) Wedge sliding and (c) Flexural toppling (Hoek and Bray, 1981).](image-url)
Rocscience Dips Version 7.0, a graphical and statistical analysis of orientation data software, was utilized to analyse and visualise the orientation data exported from CloudCompare software. The orientation data is presented in the form of stereonet, also known as stereographic projection. It can be shown in many forms such as pole vector mode, dip vector mode, contour mode, 3D stereonet and Rosette plot. Many computational features are available, such as statistical contouring of orientation clustering, mean orientation calculation and qualitative and quantitative feature attribute analysis. Kinematic analysis is one of the features that are useful in the software. The kinematic analysis feature provides a quick check for various rock slope stability failure modes on a stereonet plot such as planar sliding, wedge sliding and flexural toppling by just input the slope orientation, friction angle and lateral limits and select the failure modes. It can identify the critical percentages of potential movement of the rock blocks in various failure modes.

3.9.1 Create a Stereonet

The orientation of discontinuity that has been extracted from the rock slope using CloudCompare software was imported into Rocscience Dips Version 7.0 software. There are many types of global orientation format such as dip/dip direction, trend/plunge, and strike/dip. In this study, dip/dip direction was utilized since the orientation format obtained is in dip/dip direction as shown in Figure 3.27. Next, define the traverse information as it is used to group data units as depicted in Figure 3.28. Then, the stereonet is ready to be visualized and query.
Figure 3.27: Project settings.

Figure 3.28: Traverse information.

Figure 3.29: Stereonet plotted.
3.9.2 Add Set and Plane

With the stereonet presented, add the plane of the slope as shown in Figure 3.30. Then, add set to the stereonet based on the contour density concentration by clicking at “sets from cluster analysis” as displayed in Figure 3.31. Sets are created for the purpose of obtaining mean plane orientations and set statistics of data clusters.

![Add User Plane](image1)

Figure 3.30: Add user plane.

![Add Set from Cluster Analysis](image2)

Figure 3.31: Add set from cluster analysis.

3.9.3 Kinematic Analysis

Then, kinematic analysis can be carried out by selecting the mode of failure: planar sliding, wedge sliding and flexural toppling and by inputting the kinematic properties as depicted in Figure 3.32. The statistical results will be shown for each failure mode.
3.9.4 Sensitivity Analysis

Since a slight change in the kinematic properties: orientation, friction angle and lateral limits will affect the critical percentages of the potential failure of the rock slope, sensitivity analysis can be carried out to determine its effect by inputting a range of values of orientation, friction angle and lateral limits. Graphs are plotted to show the effects of the changes to the critical percentages of the rock slope failure. The probability of failure should be less than 25%. To determine the effect of changing the value of kinematic properties, click on the kinematic sensitivity to input the range of values as displayed in Figure 3.33.
3.10 3D 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. Groundwater, support and loading can be included in the analysis. Almost all of the existing 3D LEMs was extended from 2D slices methods. In order to convert 2D methods of slices into 3D slope stability analyses, the slices are needed to be changed into the columns by adding the third dimension. As a result, the static conditions of limit equilibriums of the columns have to be satisfied. Rocscience Slide3 analyzes the stability of 3D slip surfaces using vertical column limit equilibrium methods. It uses the general formulation of Cheng and Yip (2007), with further improvements, including: efficient solver for 3D equilibrium equations, any failure criteria can be used (not limited to Mohr-Coulomb, fast search methods for general 3D slip surfaces and powerful geometry modeling and data interpretation features.

Figure 3.34 shows a typical soil column and its related internal and external forces where for column (i,j), \( W_{i,j} \) is weight of soil, \( L_{z_{i,j}} \) is external vertical load, \( L_{x_{i,j}} \) and \( L_{y_{i,j}} \) are external horizontal loads in x- and y-directions respectively, \( F_{e_{vi,j}} \) is vertical force induced by earthquake, \( F_{eh_{xi,j}} \) and \( F_{eh_{yi,j}} \) are horizontal force induced by earthquake in x- and y-directions respectively, \( E_{xi-1,j} \) and \( E_{xi,j} \) are inter-column normal forces in x-direction, \( E_{yi,j-1} \) and \( E_{xi,j} \) are inter-column normal forces in y-direction, \( X_{xi-1,j} \) and \( X_{xi,j} \) are vertical inter-column shear forces in x-direction, \( X_{yi,j-1} \) and \( X_{xi,j} \) are vertical inter-column shear forces in y-direction, \( H_{xi-1,j} \) and \( H_{xi,j} \) are horizontal inter-column shear forces in x-direction, \( H_{yi,j-1} \) and \( H_{xi,j} \) are horizontal inter-column shear forces in y-direction, \( S_{i,j} \) is shear strength force at the base of column, and \( N_{i,j} \) and \( U_{i,j} \) are total
normal force and pore water force at the base of column respectively. Some of these forces may be ignored, simplified, or assumed in different methods.

![Diagram of forces acting on a column](image)

Figure 3.34: 3D view of forces acting on a column (Huang et al., 2002).

### 3.10.1 Build Geometry Model

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 software as shown in Figure 3.35. Then, the volume of the geometry of the rock slope was created by using the function “extended from the surface” as the geometry imported was just showing the textured surface of the rock slope.

![Rocscience Slide3 interface](image)

Figure 3.35: Rock slope geometry imported into Rocscience Slide3.
3.10.2 Limit Equilibrium Analysis Method

According to Morgenstern and Price, Morgenstern-Price or GLE analysis method with half-sine inter-column force function is used to analyse the rock slope stability as shown in Figure 3.37. Morgenstern-Price method which is based on satisfying force and moment equilibrium and assumes the inter-slice force function can be extended to a 3D method of columns, where forces and moments are solved in two orthogonal directions. Vertical forces determine the normal and shear force on the base of each column (Morgenstern and Price, 1965). The inter-slice force inclination can vary with an arbitrary function (f(x)) as depicted in equation 3.6.

\[ X = f(x) \cdot \lambda \cdot E \]  

(3.6)

X denotes the vertical shear force on the side of the slice; f(x) denotes the inter-slice force function that varies continuously along the slip surface; \( \lambda \) denotes scale factor of the assumed function and E denotes the total horizontal stress.
Each block in Figure 3.38 is assumed to contribute due to the same forces. The following assumptions are introduced in the Morgenstern-Price method to calculate the limit equilibrium of forces and moment on individual blocks: dividing planes between blocks are always vertical, the line of action of weight of block $dW$ passes through the center of the $i^{th}$ segment of slip surface, the normal force $dN$ is acting at the center of the $i^{th}$ segment of slip surface, inclination of forces $E$ acting between blocks is different on each block ($\delta_i$) and at slip surface end points is $\delta = 0$.

Choice of inclination angles $\delta$ of forces $E$ acting between the blocks is realized with the help of Half-sine function - one of the functions in Figure 3.39 is automatically selected. This choice of the shape of function has a minor influence on final results, but suitable choice can improve the convergence of method.
Figure 3.40 shows the 3D slip surface discretized into a grid of square columns with equal cross-sectional area. The discretization of a sliding mass into vertical columns is based on the following assumptions: all columns have a square cross-section of equal area and the columns are aligned with the X-Y axes. Figure 3.41 shows the data of the selected column.

![Figure 3.40: 3D slip surface discretized into square column (a) Top view, (b) View from YZ plane.](image)

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Normal Stress (kPa)</td>
<td>44.196</td>
</tr>
<tr>
<td>Base Effective Normal Stress (kPa)</td>
<td>44.196</td>
</tr>
<tr>
<td>Pore Pressure (kPa)</td>
<td>0.000</td>
</tr>
<tr>
<td>Initial Pore Pressure (kPa)</td>
<td>0.000</td>
</tr>
<tr>
<td>Shear Strength (kPa)</td>
<td>30.517</td>
</tr>
<tr>
<td>Shear Stress (kPa)</td>
<td>33.612</td>
</tr>
<tr>
<td>Base Shear Force (kN)</td>
<td>61.759</td>
</tr>
<tr>
<td>Base Normal Force (kN)</td>
<td>81.206</td>
</tr>
<tr>
<td>Base Cohesion (kPa)</td>
<td>5.000</td>
</tr>
<tr>
<td>Base Friction Angle (deg)</td>
<td>30.000</td>
</tr>
<tr>
<td>Column Weight (kN)</td>
<td>125.008</td>
</tr>
<tr>
<td>Column Volume (m³)</td>
<td>4.808</td>
</tr>
<tr>
<td>Column Weight/Area (kN/m²)</td>
<td>91.920</td>
</tr>
<tr>
<td>Dip of Column Base (deg)</td>
<td>42.254</td>
</tr>
<tr>
<td>Dip Direction of Column Base (deg)</td>
<td>188.711</td>
</tr>
<tr>
<td>Matric Suction (kPa)</td>
<td>0.000</td>
</tr>
<tr>
<td>Column Center(X,Y) (m)</td>
<td>7.520, 52.459</td>
</tr>
<tr>
<td>Column Center Z Top (m)</td>
<td>24.720</td>
</tr>
<tr>
<td>Column Center Z Bottom (m)</td>
<td>21.111</td>
</tr>
</tbody>
</table>

Figure 3.41: Inter-column data.
3.10.3 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. In this study, the intact rock mass was defined using Generalised Hoek-Brown Failure Criterion. Since rock mass has discontinuities, generalized anisotropic was used to define the orientations of the anisotropic plane in the rock slope. The weak joint was defined by Mohr Coulomb Failure Criterion. Figure 3.42 shows the way to access define materials.

![Figure 3.42: Define materials.](image)

3.10.3.1 Generalised Hoek-Brown Failure Criterion

The rock mass materials were defined using Generalised Hoek-Brown Failure Criterion. The values of the parameters were obtained from the laboratory test and the rock database in Rocscience RocData.

![Figure 3.43: Rock mass parameters.](image)
3.10.3.2 Generalised Anisotropic Strength Model

The Generalized Anisotropic Strength model allows you to define anisotropic strength properties for a material using any combination of failure criteria applied over different orientations. Dip / dip direction was used to define the anisotropy as shown in Figure 3.44. Two joint sets were identified and used. A simple diagram of two joint sets is displayed in Figure 3.45. The A and B parameters define the angular range of the anisotropy. The failure criterion used to define the material in the weak joint is Mohr Coulomb as discussed.

Figure 3.44: Angle of anisotropic plane.

Figure 3.45: Two anisotropic planes in the slope.
A 2D representation of the A and B parameters is shown in Figure 3.46. If a shear plane lies within angle A, the anisotropic plane strength is applied. If a shear plane lies outside of angle B, the rock mass strength is applied. If a shear plane lies between angle A and B, a linear transition between the rock mass strength and the anisotropic plane strength is applied. Figure 3.47 illustrates how the shear strength is derived for a Generalized Anisotropic material in the form of graph.

Figure 3.46: 2D representation of A and B angle parameters.

Figure 3.47: Graph of shear strength against the angle of anisotropy.
3.10.3.3 Mohr Coulomb Failure Criterion

Discontinuities in the rock mass will be filled up with anisotropic material which does not have the same strength as the intact rock. Their strength is weak and will induce rock slope failure. The anisotropic material is defined by Mohr Coulomb Failure Criterion as shown in Figure 3.48.

Figure 3.48: Anisotropic material parameters.

3.10.4 Assign Material

After defining all the rock materials, the correct material has to be assigned to the rock geometry. In our 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 which is dipping at an angle as depicted in Figure 3.49.

Figure 3.49: Assign material to the rock geometry.
3.10.5 3D 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 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. If they have a lower FoS, they will replace the solution in that nest. A small percent of the worst solutions in the ‘n’ nests will be thrown away and replaced by completely random new solutions. This process is repeated for a finite number of iterations. The Schematic illustration of Cuckoo Search algorithm is shown in Figure 3.50. 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.

Figure 3.50: Schematic diagram of Cuckoo Search algorithm.
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. Figure 3.51 depicts the way to click on the slip surface options.

![Figure 3.51: 3D Slip surface options.](image)
3.10.6 Compute 3D Slope Stability Results

Next, the deterministic analysis was computed as illustrated in Figure 3.52 and the outcome will be the global minimum slip surface and the FoS of the entire rock slope as depicted in Figure 3.53. The display of the slip surfaces can be filtered based on the FoS.

Figure 3.52: Computation of results.

Figure 3.53: Results output of 3D analysis.
3.11 2D Limit Equilibrium Rock Slope Stability Analysis

From the 3D rock slope stability analysis, a critical global minimum slip surface of the rock slope will be identified. Then, the 2D section of the global minimum slip surface can be extracted and analysed in 2D analysis using probabilistic method where the least FoS will be analysed. The 2D analysis was carried in Rocscience Slide Version 2018 in which it 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.

3.11.1 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 of the plane was extracted in Rocscience Slide3 software and exported into Rocscience Slide software for 2D limit equilibrium stability analysis as shown in Figure 3.54.

Figure 3.54: Section export from Rocscience Slide3 to Slide.
3.11.2 Limit Equilibrium Analysis Method

Morgenstern-Price or GLE analysis method with half-sine inter-slice force function is used to analyse the 2D rock slope stability as shown in Figure 3.55. Figure 3.56 depicts the slice data of the Morgenstern-Price method.

---

![Project Settings](image1.png)

**Figure 3.55:** 2D rock slope stability analysis method.

![Slice Data](image2.png)

**Figure 3.56:** Slice data from Morgenstern-Price method.
3.11.3 Define Rock Slope Material

Figure 3.57 shows the way to click on “Define Materials” from the Properties tab. 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. Similar to 3D analysis, the intact rock mass is defined using Generalised Hoek-Brown Failure Criterion as shown in Figure 3.58. Since rock mass has discontinuities, generalized anisotropic was used to define the orientations of the anisotropic plane in the rock slope as displayed in Figure 3.59 and Figure 3.60. The weak joint was defined by Mohr Coulomb Failure Criterion as set in Figure 3.61.

Figure 3.57: Define materials.

Figure 3.58: Rock mass parameters – Generalised Hoek-Brown Failure Criterion.
Figure 3.59: Anisotropic Plane – Generalised Anisotropic Strength Model.

Figure 3.60: Angle of anisotropic plane.

Figure 3.61: Anisotropic material parameter – Mohr Coulomb Failure Criterion.
3.11.4 Assign Material

After defining all the rock materials, the correct material has to be assigned to the rock geometry. In our 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 which is dipping at an angle as shown in Figure 3.62.

![Assign Material](image)

Figure 3.62: Assign material to the rock section plane.

3.11.5 Probabilistic Analysis

Deterministic analysis renders a single value of FoS by assuming the values of all model input parameters are exactly known. Nevertheless, in reality, rock slope is heterogeneous and the parameters are varies 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. By assigning a statistical distribution to one or more model input parameters, the degree of uncertainty in the value of the parameters are accounted. Input data samples are randomly generated based on the statistical distributions. A given slip surface may then have many different values of safety factor calculated. As a result, a distribution of FoS and probability of failure of the slope can be calculated.
Each input parameter that is defined as a random variable is sampled according to the statistical distribution defined for the variable, the sampling method and the number of samples. This generates N values of each random variable (where N = number of samples). As shown in Figure 3.63, each iteration of the probabilistic analysis is carried out by loading a new set of random variable samples, and re-running the analysis. This is repeated N times where N = Number of Samples.

![Diagram of random variable samples](image)

Figure 3.63: Random variable samples used in probabilistic analysis.

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.
To carry out probabilistic analysis, the function has to be checked in the project settings as shown in Figure 3.64. Then, the statistical distributions are set for material parameters as displayed in Figure 3.65. A range of values of the parameters are set for random computation of the FoS. The outcome will be the global minimum surface with deterministic FoS, mean FoS of the probabilistic method, probability of failure and reliability index.

![Project Settings](image1)

Figure 3.64: Probabilistic analysis.

![Material Statistics](image2)

Figure 3.65: Material statistics for probability analysis.
3.11.6 2D Slip Surface Search Method

Similar to 3D slip surface search method, the slip surface was searched using Cuckoo Search Method with surface altering optimization in 2D analysis. The non-circular slip surface type was selected due to the anisotropic plane (discontinuity) in the rock slope as depicted in Figure 3.66.

![Figure 3.66: 2D slip surface option.](image-url)
3.11.7 Compute 2D Slope Stability Result

The deterministic and probabilistic analysis was computed as shown in Figure 3.67 and the outcome will be the global minimum slip surface and the FoS of the section of the rock slope as illustrated in Figure 3.68. The display of the slip surfaces can be filtered based on the FoS.

Figure 3.67: Computation of Results for 2D section of rock slope.

Figure 3.68: Results output from 2D analysis.
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

This chapter discusses the results and data obtained from the fieldwork at the slope in USM Main Campus and the rock slope in Perlis. The slope in USM Main Campus was studied to determine the effect of flying height on the accuracy of the results (RMSE) as well as the difference between the bundle adjustment of images with GCP and without GCP. The slope was chosen to study the accuracy assessment since it can be accessed easily.

At the rock slope in Perlis, the optimum approach identified in the study of the slope in USM Main Campus is applied in the mapping of the study area. Bundle adjustment of image dataset without and with GCP is compared as well. In addition, the discontinuity orientations of the rock outcrop were measured using geological compass. The photogrammetric data output, dense point cloud was imported into CloudCompare to extract the geological planes automatically using FACET plugin. The geological planes extracted digitally were verified by the data measured manually. Then, the discontinuity orientations were extracted and imported into Rocscience Dips to plot a stereographic projection as well as to carry out kinematic analysis such as planar sliding, wedge sliding and flexural toppling. The probability of failure of each mode of failure can be identified. The mean dip / dip direction is known from the stereonet. Another photogrammetric data output, 3D model geometry was imported into Rocscience Slide3 to conduct deterministic limit equilibrium rock slope stability analysis in 3D. The rock slope parameters are obtained via laboratory test and rock database in Rocscience RocData. The mean dip / dip direction was also acts as an input
for anisotropic plane. The critical FoS can be obtained with the global minimum slip surface. The cross section on the global minimum slip surface was extracted and imported into Rocscience Slide 2018 for 2D analysis. Probabilistic and deterministic methods were applied in 2D analysis, rendering the least FoS respectively.
4.2 Photogrammetric Data Analysis

The image datasets of the slope in USM Main Campus and rock slope in Perlis have gone through a list of photogrammetric processes and the outputs are discussed in Section 4.2.1 and Section 4.2.2 respectively.

4.2.1 Slope in USM Main Campus

Structure from Motion (SfM) photogrammetry was carried out to map an open field area with a gentle slope in USM. The coverage area of the mapping survey is 25600m². Research was carried out in this study area to determine the accuracy of using photogrammetry analysis for slope mapping with and without ground control points (GCPs). Datasets with three different flying heights measured from the same take-off point were processed with and without GCP respectively for comparisons. The three flying heights were 50m, 70m and 80m. The focal length of the camera mounted on the UAV was maintained at 8.8mm. Hence the angle view of each flying height was the same during aerial image acquisition. Table 4.1 shows the number of images captured for each mission at different flying height for the coverage area of 48600m². 10 markers were distributed on the slope with 7 markers acted as GCP as outlined in Table 4.2 and 3 markers acted as checkpoints (CPs) as listed in Table 4.3. Figure 4.1 depicts the location of the markers. A scale bar acted as a checker was prepared as well on the slope by measuring the length between the two markers. The front and side overlapping ratio was 80% and 70% respectively. To cover the same size area, more images were captured for a lower flying height. All the images were taken from the top with gimbal pitch facing downwards at -90° as displayed in Figure 4.2.
Table 4.1: Number of images captured at various flying heights.

<table>
<thead>
<tr>
<th>Flying Height (m)</th>
<th>Number of images</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>74</td>
</tr>
<tr>
<td>70</td>
<td>45</td>
</tr>
<tr>
<td>80</td>
<td>33</td>
</tr>
</tbody>
</table>

Figure 4.1: Location of markers at the slope in USM Main Campus.

Table 4.2: Coordinates of GCPs at the slope in USM Main Campus.

<table>
<thead>
<tr>
<th>GCP</th>
<th>Latitude (m)</th>
<th>Longitude (m)</th>
<th>Altitude – Mean Sea Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>5.361794</td>
<td>100.308963</td>
<td>2.4981</td>
</tr>
<tr>
<td>Point 3</td>
<td>5.361267</td>
<td>100.308313</td>
<td>9.3624</td>
</tr>
<tr>
<td>Point 5</td>
<td>5.361771</td>
<td>100.308576</td>
<td>6.8458</td>
</tr>
<tr>
<td>Point 6</td>
<td>5.361396</td>
<td>100.308033</td>
<td>17.9836</td>
</tr>
<tr>
<td>Point 7</td>
<td>5.362202</td>
<td>100.308511</td>
<td>9.1804</td>
</tr>
<tr>
<td>Point 9</td>
<td>5.362101</td>
<td>100.308080</td>
<td>17.6515</td>
</tr>
<tr>
<td>Point 10</td>
<td>5.361657</td>
<td>100.307884</td>
<td>21.0656</td>
</tr>
</tbody>
</table>

Table 4.3: Coordinates of CPs at the slope in USM Main Campus.

<table>
<thead>
<tr>
<th>CP</th>
<th>Latitude (m)</th>
<th>Longitude (m)</th>
<th>Altitude – Mean Sea Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 2</td>
<td>5.361453</td>
<td>100.308708</td>
<td>3.0666</td>
</tr>
<tr>
<td>Point 4</td>
<td>5.361323</td>
<td>100.308209</td>
<td>12.2802</td>
</tr>
<tr>
<td>Point 8</td>
<td>5.362229</td>
<td>100.308318</td>
<td>12.6819</td>
</tr>
</tbody>
</table>
4.2.1.1 Quantitative RMSE Accuracy Assessment

Table 4.4 depicts the average camera location error for bundle adjustment without GCP at various flying heights. The maximum error for X-axis is 0.491m (50m) whereas the minimum is 0.216m (80m). For Y-axis, the maximum error is 0.341m (50m) and minimum error is 0.264m (80m). The maximum and minimum error for Z-axis is 0.583m (70m) and 0.351m (80m) respectively. The maximum XY error is 0.598 (50m) while minimum is 0.341 (80m). The maximum total error is 0.763m (70m) and minimum total error is 0.489m (80m).

Table 4.4: Average camera location errors for bundle adjustment without GCP at different flying heights.

<table>
<thead>
<tr>
<th>Flying Height (m)</th>
<th>X error (m)</th>
<th>Y error (m)</th>
<th>Z error (m)</th>
<th>XY error (m)</th>
<th>Total error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.491</td>
<td>0.341</td>
<td>0.435</td>
<td>0.598</td>
<td>0.740</td>
</tr>
<tr>
<td>70</td>
<td>0.389</td>
<td>0.302</td>
<td>0.583</td>
<td>0.492</td>
<td>0.763</td>
</tr>
<tr>
<td>80</td>
<td>0.216</td>
<td>0.264</td>
<td>0.351</td>
<td>0.341</td>
<td>0.489</td>
</tr>
</tbody>
</table>

Figure 4.2: Aerial images of the slope in USM Main Campus captured using UAV.
Figure 4.3 illustrates the average camera location errors for bundle adjustment without GCP at various heights. RMSE is seemed to be increasing with lower flying heights. This pattern is inaccurate as lower flying height should render lesser RMSE due to better ground sampling distance. The occurrence of this phenomenon might be due to the low accuracy of the navigation system of the UAV. The GPS in UAV is having an accuracy of about 2m, which is not accurate for direct geo-referencing. The random RMSE value happens due to the lack of geometric constraints of calculating aerial-triangulation which was because the RMSE depended on the accuracy of the UAV’s navigation system where correction is not applied instantaneously.

Table 4.5: RMSE of GCPs for bundle adjustment with GCPs at different flying heights.

<table>
<thead>
<tr>
<th>Flying Height (m)</th>
<th>X error (m)</th>
<th>Y error (m)</th>
<th>Z error (m)</th>
<th>XY error (m)</th>
<th>Total error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.1080</td>
<td>0.0681</td>
<td>0.0395</td>
<td>0.1277</td>
<td>0.1337</td>
</tr>
<tr>
<td>70</td>
<td>0.1073</td>
<td>0.0766</td>
<td>0.0385</td>
<td>0.1318</td>
<td>0.1374</td>
</tr>
<tr>
<td>80</td>
<td>0.1088</td>
<td>0.0788</td>
<td>0.0572</td>
<td>0.1343</td>
<td>0.1460</td>
</tr>
</tbody>
</table>
Based on Table 4.5 which shows the Root Mean Square Error (RMSE) of GCPs and CPs for bundle adjustment with GCPs at different flying height, the maximum error of GCPs in X-axis is 0.1088m (80m) whereas the minimum is 0.1073m (70m). For Y-axis, the maximum error for GCPs is 0.0788m (80m) and minimum error is 0.0681m (50m). The maximum and minimum error of GCP in Z-axis is 0.0572m (80m) and 0.0385m (70m) respectively. The maximum XY error for GCP is 0.1343 (80m) while minimum is 0.1277 (50m). The maximum total error for GCP is 0.1460m (80m) and minimum total error for GCP is 0.1337m (50m). The graph of RMSE of GCPs is illustrated in Figure 4.4. The difference of XY error is 0.66cm. On the other hand, Z error has a slightly higher difference of 1.87cm. The total error difference is 1.23cm. Hence, the difference in errors of GCPs for each flying heights is very small. However, there is a general trend as shown in Figure 4.5 where lower flying height will induce lower errors because ground sampling distance of the images decreases.

Figure 4.4: Graph of RMSE of GCPs at different axis at various flying heights.
Table 4.6: RMSE of CPs.

<table>
<thead>
<tr>
<th>Flying Height (m)</th>
<th>X error (m)</th>
<th>Y error (m)</th>
<th>Z error (m)</th>
<th>XY error (m)</th>
<th>Total error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.0584</td>
<td>0.0522</td>
<td>0.1065</td>
<td>0.0784</td>
<td>0.1322</td>
</tr>
<tr>
<td>70</td>
<td>0.0238</td>
<td>0.0301</td>
<td>0.0854</td>
<td>0.0384</td>
<td>0.0936</td>
</tr>
<tr>
<td>80</td>
<td>0.0422</td>
<td>0.0395</td>
<td>0.0385</td>
<td>0.0578</td>
<td>0.0694</td>
</tr>
</tbody>
</table>

For CPs which is used to verify the GCPs as shown in Table 4.6, the maximum error in X-axis is 0.0584m (50m) while minimum error is 0.0422m (80m). For Y-axis, the maximum error of CP is 0.0522m (50m) and the minimum error is 0.0301m (70m). The maximum and minimum Z error of CP is 0.1065m (50m) and 0.0385m (80m) respectively. The maximum XY error of CP is 0.0784m (50m) whereas minimum is 0.0578m (80m). Lastly, 0.1322m (50m) and 0.0694m (80m) are the maximum and minimum total error for CP respectively. The graph of RMSE of GCPs with its CPs is presented in Figure 4.6. The graph shows that all the RMSE of CPs is lower than that of GCPs. This has verified that the GCPs are reliable on bundle adjustment of the images.
Another method to verify the accuracy of the GCP is by allocating a scale bar on the mapping area. The actual length measured between two points, Point 11 and Point 12 is 42.8m. However, there is some difference between the actual lengths measured on site with the lengths measured in the dense point cloud produced from bundle adjustment of the images captured at various heights. The distance errors for various heights are tabulated in Table 4.7. The difference in error is 0.48cm in which all errors is ±4cm.

Table 4.7: RMSE of check scale bar at different flying height.

<table>
<thead>
<tr>
<th>Flying Height (m)</th>
<th>Distance (m)</th>
<th>Distance error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>42.8335</td>
<td>0.0335</td>
</tr>
<tr>
<td>70</td>
<td>42.8383</td>
<td>0.0383</td>
</tr>
<tr>
<td>80</td>
<td>42.8337</td>
<td>0.0337</td>
</tr>
</tbody>
</table>
Table 4.8: Comparison of total RMSE with and without GCP at various flying heights.

<table>
<thead>
<tr>
<th>Flying Height (m)</th>
<th>Total RMSE (m)</th>
<th>(\text{Without GCP})</th>
<th>(\text{With GCP})</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.7400</td>
<td>0.1337</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>0.7630</td>
<td>0.1374</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>0.4890</td>
<td>0.1460</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.9: DSM resolution of bundle adjustment with and without GCP.

<table>
<thead>
<tr>
<th>Flying Height (m)</th>
<th>Resolution (cm/pix)</th>
<th>(\text{Without GCP})</th>
<th>(\text{With GCP})</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>6.66</td>
<td>6.91</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>8.80</td>
<td>9.11</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>9.88</td>
<td>10.10</td>
<td></td>
</tr>
</tbody>
</table>

To have a clearer view on the difference between bundle adjustment with and without GCP, the total RMSE for both with and without GCP at various flying heights is tabulated in Table 4.8. Undoubtedly, the dataset processed with GCP has less error than that without GCP because all the images undergo photo alignment optimization with the coordinates obtained from a handheld RTK-GNSS instrument which receives single L1 signal. The images are geo-referenced accurately. On the other hand, the photos aligned without GCP undergoes photo alignment with the coordinates obtained from its built-in GPS in the UAV. The accuracy of the built-in GPS is not as good as the RTK-GNSS instrument. Besides that, the variation of flying heights has an impact on the resolution of the map produced from the photogrammetry. Higher resolution indicates lower size per pixel (cm/pixel). The resolution of the map increases when the flying height decreases. Hence, RMSE is reduced when flying height is lower. The DSM resolutions for various heights are displayed in Table 4.9. In short, the flying height of the UAV to capture the images must be as low as possible depends on the site
condition, size of the mapping area and project purpose. The images must be processed using GCPs as coordinate to geo-reference all the images for constructing dense point cloud, 3D model, orthophoto and digital surface model (DSM) which can be used for further measurement and analysis work.

4.2.1.2 Qualitative Accuracy Assessment

The photogrammetric process can produce dense point cloud, 3D textured model, orthophoto and Digital Surface Model (DSM). Orthophoto can be exported in Google KMZ file and overlay on the image in Google Earth Pro. It can be seen clearly in Figure 4.7a where the road on the orthophoto connects the road on the Google Earth Pro accurately. On the other hand, the road is not aligned in Figure 4.7b where the orthophoto is produced without GCP. Although the accuracy of Google Earth Pro is low with horizontal RMSE 1.59m (Mohammed et al., 2013), it can still be used for a preliminary guideline and visualization purpose. This situation indicates that the coordinates of the GCP are highly accurate and processing the photogrammetric data using GCP is beneficial. The accuracy of the three different flying heights processed with GCP can be claimed to be high and better than that without GCP.

Figure 4.7: Orthophoto of 80m flying height overlaid on Google Earth Pro (a) with GCP, (b) without GCP (Google Earth Pro, 2018) [2nd February 2018].
Moreover, DSM produced using GCP and without GCP is different. Figure 4.8a shows that the DSM produced with GCP and Figure 4.8b depicts the DSM produced without GCP. The lower and upper limit of the elevation is having a huge difference. This is because the built-in GPS has a high error in giving the altitude of the images. Therefore, GCP is utilised to geo-reference all the images captured before processing the dataset. Conclusion can be made to claim that GCP is very pivotal in producing a high accuracy photogrammetric output which is useful for further analysis.

Figure 4.8: DSM of 80m flying height (a) with GCP, (b) without GCP.
4.2.2 Rock Slope in Perlis

Structure from Motion (SfM) photogrammetry was carried out to map the 27700m$^2$ rock slope. 74 images were taken using UAV from the top of the rock slope as shown in Figure 4.9 and 160 images were captured from the side of the rock slope as displayed in Figure 4.10. More photos were taken from the side of the rock slope to increase the number of photos overlapping, increasing the points in the dense point cloud and thus enhancing the texture of the 3D model. The front and side overlapping ratio is 80% and 70% respectively. A total of 10 GCPs are used as a reference for photo bundle adjustment as tabulated in Table 4.10. The locations of the GCPs are depicted in Figure 4.11.

![Figure 4.9: Aerial images of the rock slope in Perlis captured using UAV.](image)

![Figure 4.10: Side images of the rock slope in Perlis captured using UAV.](image)
Table 4.10: Coordinates of GCPs for Rock Slope in Perlis.

<table>
<thead>
<tr>
<th>GCP</th>
<th>Latitude (m)</th>
<th>Longitude (m)</th>
<th>Altitude – Mean Sea Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>6.428421</td>
<td>100.144337</td>
<td>2.493</td>
</tr>
<tr>
<td>P2</td>
<td>6.428434</td>
<td>100.144404</td>
<td>1.634</td>
</tr>
<tr>
<td>P3</td>
<td>6.428742</td>
<td>100.144417</td>
<td>2.991</td>
</tr>
<tr>
<td>P4</td>
<td>6.428693</td>
<td>100.144744</td>
<td>4.131</td>
</tr>
<tr>
<td>P5</td>
<td>6.428660</td>
<td>100.144930</td>
<td>3.917</td>
</tr>
<tr>
<td>P6</td>
<td>6.428645</td>
<td>100.145312</td>
<td>3.987</td>
</tr>
<tr>
<td>P7</td>
<td>6.428899</td>
<td>100.144622</td>
<td>25.246</td>
</tr>
<tr>
<td>P8</td>
<td>6.428869</td>
<td>100.144940</td>
<td>25.749</td>
</tr>
<tr>
<td>P9</td>
<td>6.428998</td>
<td>100.144622</td>
<td>33.253</td>
</tr>
<tr>
<td>P10</td>
<td>6.428974</td>
<td>100.144784</td>
<td>33.657</td>
</tr>
</tbody>
</table>

Figure 4.11: Location of GCP markers at the rock slope in Perlis.

Agisoft Photoscan Professional software was utilized to process the acquired data images. A total of 234 images were used for bundle adjustment and producing a high quality dense point cloud and 3D model. Besides dense cloud and 3D textured model, the photogrammetry process can produce high quality orthophoto and Digital Surface Model (DSM). Contour at our preference interval can be generated from the
DSM as well. Each outcome of the photogrammetry process has its own usages and functions. Dense point cloud as displayed in Figure 4.12 created is useful as it is needed to create a 3D model. Denser point cloud will render a more textured and finer model. Besides, it can be exported to software, CloudCompare to extract its geological planes according to its orientations. 3D model as depicted in Figure 4.13 generated can be exported to third party software for rock slope stability analysis. In this study, it is exported to Rocscience Slide3 (RS$^3$) software that can carry out limit equilibrium analysis on the rock slope. DSM as given in Figure 4.14 is produced to visualise the elevation of the rock slope. It can be exported into Global Mapper software to analyse the elevation of each location and extract the coordinates for further analysis. Contour generated from DSM as shown in Figure 4.15 can be utilised for other planning as well such as rock slope cut and fill. Lastly, orthophoto which can be produced according to its scale and coordinates can be exported and overlaid on Google Earth Pro for visualization purpose as shown in Figure 4.16. Since the model is geo-referenced and created with scale, length, area and volume of the study area can be measured in the interactive 3D space model.

![Figure 4.12: Dense point cloud of the rock slope (Top View).](image)
Figure 4.13: 3D textured model of the rock slope (Top View).

Figure 4.14: Digital Surface Model (DSM) of the rock slope.

Figure 4.15: Contour generated at 5m interval.
4.2.2.1 **Comparison of Bundle Adjustment with and without GCPs**

The images captured by the UAV were processed without and with GCPs to see if there is any significant difference between the two variables. Without GCPs, the images are aligned according to their own positions respectively since each photo is geo-referenced by the built-in GPS in the UAV device. On the other hand, with GCPs, the images are aligned accordingly to the coordinates obtained from RTK-GNSS without considering the positions of the camera. From Table 4.11, there is a significant reduction, nearly 80% in Root-Mean-Square Error (RMSE) if the images are aligned with GCP compared to images aligned without GCP. The total RMSE obtained for the case of with GCP is 21cm which is acceptable as the GPS instrument can only receive single frequency, L1 signal. Moreover, the RMSE for control scale bar is 12mm as shown in Table 4.12. Hence, GCP plays a critical role in increasing the accuracy of the results and this method must be applied in conducting photogrammetry for data acquisition of the topography.
Table 4.11: Comparison of RMSE between bundle adjustment without and with GCPs.

<table>
<thead>
<tr>
<th>Bundle Adjustment</th>
<th>X error (m)</th>
<th>Y error (m)</th>
<th>Z error (m)</th>
<th>XY error (m)</th>
<th>Total error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without GCP</td>
<td>0.6932</td>
<td>0.5225</td>
<td>0.6292</td>
<td>0.8681</td>
<td>1.0721</td>
</tr>
<tr>
<td>With GCP</td>
<td>0.1461</td>
<td>0.1047</td>
<td>0.1074</td>
<td>0.1797</td>
<td>0.2094</td>
</tr>
</tbody>
</table>

Table 4.12: RMSE of control scale bars.

<table>
<thead>
<tr>
<th>Label</th>
<th>Distance (m)</th>
<th>Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1_P2</td>
<td>7.4351</td>
<td>-0.0048954</td>
</tr>
<tr>
<td>P3_P4</td>
<td>36.9484</td>
<td>-0.0115581</td>
</tr>
<tr>
<td>P4_P5</td>
<td>20.9617</td>
<td>-0.0182788</td>
</tr>
<tr>
<td>P5_P6</td>
<td>42.337</td>
<td>0.0169887</td>
</tr>
<tr>
<td>P9a_P10a</td>
<td>5.5544</td>
<td>0.0094210</td>
</tr>
<tr>
<td>P11_P12</td>
<td>1.2714</td>
<td>-0.0026419</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.0120832</td>
</tr>
</tbody>
</table>

Figure 4.17: DSM of rock slope with six yellow lines as cross sections.
Figure 4.18: Comparison of elevation between dataset without and with GCPs for (a) line 1, (b) line 2, (c) line 3, (d) line 4, (e) line 5 (f) and line 6.
Table 4.13: Coordinates of Cross-Sections.

<table>
<thead>
<tr>
<th>Line</th>
<th>From</th>
<th>To</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude (m)</td>
<td>Longitude (m)</td>
</tr>
<tr>
<td>L1</td>
<td>6.4293107</td>
<td>100.1446724</td>
</tr>
<tr>
<td>L2</td>
<td>6.4293107</td>
<td>100.1447724</td>
</tr>
<tr>
<td>L3</td>
<td>6.4293107</td>
<td>100.1448724</td>
</tr>
<tr>
<td>L4</td>
<td>6.4293107</td>
<td>100.1449724</td>
</tr>
<tr>
<td>L5</td>
<td>6.4293107</td>
<td>100.1450724</td>
</tr>
<tr>
<td>L6</td>
<td>6.4293107</td>
<td>100.1451724</td>
</tr>
</tbody>
</table>

DSM for 3D model with GCPs are produced and shown in Figure 4.17. Graphs of elevation of rock slope against distance are plotted in Figure 4.18 for six different lines where the coordinates of the lines are tabulated in Table 4.13. Using the same coordinates for both DSM without and with GCPs, it can be clearly seen that there is a difference of nearly 10m elevation for all the six lines. This phenomenon indicates that GCPs will render better results in term of accuracy since it has undergone bundle adjustment optimization based on the global coordinates measured by RTK-GNSS instrument, followed by a dense geometry reconstruction. Without GCPs, the dense geometry reconstruction is based on the geo-tagged positions as recorded by the UAV on-board data logger which has higher errors in terms of altitude measurement.

4.3 Discontinuity Orientation of Rock Slope

Two methods were applied in acquiring the orientation of discontinuity (dip/dip direction) of the rock slope: manual approach by using scanline survey method and automatic approach by extracting the discontinuity orientation of the rock slope digitally. The scanline survey method is used to verify the reliability and accuracy of the discontinuity orientation extracted digitally.
4.3.1 Scanline Survey Method

The dip / dip direction of the rock slope was measured along the three lines at different elevations as shown in Figure 4.19. The results of the 30 sets of dip / dip directions were tabulated in Table 4.14.

Table 4.14: Dip / Dip direction obtained from scanline survey method.

<table>
<thead>
<tr>
<th>Line</th>
<th>Location</th>
<th>Dip Angle (°)</th>
<th>Dip Direction (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>51</td>
<td>175</td>
</tr>
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<td>2</td>
<td>64</td>
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<td></td>
</tr>
<tr>
<td>3</td>
<td>60</td>
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<tr>
<td>4</td>
<td>78</td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>76</td>
<td>185</td>
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</tr>
<tr>
<td>6</td>
<td>64</td>
<td>190</td>
<td></td>
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<tr>
<td>7</td>
<td>42</td>
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<td>8</td>
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<td></td>
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<tr>
<td>10</td>
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<td>175</td>
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<tr>
<td>11</td>
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</tr>
<tr>
<td>12</td>
<td>55</td>
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<td>13</td>
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<td>16</td>
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<td>17</td>
<td>41</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>Second</td>
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<td></td>
<td></td>
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<tr>
<td>1</td>
<td>39</td>
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<td>41</td>
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<td>39</td>
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</tr>
<tr>
<td>Third</td>
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<td></td>
<td></td>
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<tr>
<td>1</td>
<td>46</td>
<td>171</td>
<td></td>
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<tr>
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<tr>
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<td>46</td>
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<td>190</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>174</td>
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</tr>
</tbody>
</table>
Figure 4.19: Orientations were measured along the three lines.

4.3.2 Extraction of Geological Planes

In CloudCompare, FACET plugin was used to extract the discontinuities present in the rock mass. 31 million points out of 59 million points belong to the outcrop. After the process of fast marching (FM) approach in plane segmentation, 3852 facets were produced and grouped according to their dip / dip directions. From Figure 4.20a and Figure 4.20b, it can be noticed that there are two major discontinuity sets: Set 1 (green) and Set 2 (blue). The mean dip/dip direction for Set 1 is 046°/172° as displayed in Figure 4.21a whereas for Set 2, it is 043°/189° as shown in Figure 4.21b. For the entire rock slope, the mean dip/dip direction is 035°/186° as depicted in Figure 4.21c. The stereograms shown in Figure 4.21, exported from CoudCompare, were plotted in dip vector mode.
Figure 4.20: Facets extracted from 3D dense cloud using FACET plugin in CloudCompare (a) Top view, (b) Front view.

Figure 4.21: Stereogram (a) Green set, (b) Blue set, (c) Entire rock slope.
4.3.3 Dip / Dip Direction Analysis

Manual measurement of orientations using scanline survey method was used to verify the accuracy of the extraction of geological planes by FACET plugin in CloudCompare. The dip / dip direction of the same location was extracted from the software to compare with that obtained manually. The data is tabulated in Table 4.15.

Table 4.15: Comparison of dip / dip direction obtained manually and from software.

<table>
<thead>
<tr>
<th>Line</th>
<th>Location</th>
<th>Scanline Survey</th>
<th>Extraction from Software</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dip Angle (°)</td>
<td>Dip Direction (°)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dip Angle (°)</td>
<td>Dip Direction (°)</td>
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<td>Dip Direction (°)</td>
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<td>Dip Angle (°)</td>
<td>Dip Direction (°)</td>
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<td>52</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>174</td>
</tr>
</tbody>
</table>
Figure 4.22: Stereogram of orientations measured by scanline survey method.

Figure 4.23: Stereogram of orientations extracted from CloudCompare software.

From Table 4.15, there is a difference of up to 7° of dip angle and dip direction between the data extracted digitally from the software and manual measurement.
Stereogram of orientations measured by scanline survey method and extracted digitally from software are depicted in pole vector mode in Figure 4.22 and Figure 4.23 respectively. Both stereograms show a quite similar contours of pole vectors, facing north in the stereogram. The mean dip / dip directions measured by manual measurement is $047^\circ/180^\circ$ whereas $048^\circ/181^\circ$ for dip / dip directions extracted from software. The difference is about $1^\circ$. Despite of the difference of up to $7^\circ$ in the individual poles, the results are acceptable and within the tolerance limit for both dip angle and dip direction since the natural outcrop roughness contributes to the variability. Hence, this indicates that FACET plugin in CloudCompare can extract geological planes accurately based on its algorithm. It performed well to map explicitly the entire rock outcrop. All the facets extracted from the entire rock outcrop is useful for further rock slope stability analysis. Figure 4.24 shows the stereogram of 2933 pole vectors extracted from the entire rock slope with mean set plane of $043^\circ/185^\circ$.

Figure 4.24: Stereogram of all pole vectors extracted from CloudCompare software.
Normally, scanline methods are carried out at the human height level from the ground due to accessibility limitations to the higher portion of the rock slope. There might be different orientations at the bottom and upper portion of the rock slope. Thus, without obtaining data from the rock slope which is inaccessible, the data collected might be bias and cannot represent the entire rock slope. Using photogrammetry to obtain rock outcrop is a better approach in reducing bias and getting reliable results. Furthermore, the extraction of geological planes mainly depends on the quality of the SfM dense point cloud produced. In this study, high quality dense point cloud is constructed and the original pixel count is divided by 4 (image width and height each divided by 2). This value indicates that for an image with 20 megapixels, it will be turned into a 5 megapixels image. Lower dense point cloud density will result in lower quality of planes extraction due to smoothened edge. Textures in the rock mass are not sharp and therefore results obtained will be inaccurate.
4.4 Rock Mass Properties

The rock mass properties were determined via laboratory test and the rock database. Uniaxial Compressive Test was conducted to determine the uniaxial compressive strength (UCS) of the rock. For other geotechnical input parameters, Rocscience RocData Version 5.0 was used as to acquire the rock material properties. It enables users to easily visualize the effects of changes in input parameters on rock failure envelopes.

4.4.1 UCS Test Result

The two limestone rock samples shown in Figure 4.25 are used for uniaxial compressive strength (UCS) test. Two specimens with a diameter of 50mm and height of 100mm are cored and trimmed from each rock as displayed in Figure 4.26a. The area, weight, maximum load and maximum stress of the rock specimens are recorded in Table 4.16. Figure 4.25b shows the crack of the rock specimens after the test. By visualizing the specimens before and after the test, the fractures occur near to the existing discontinuity of the rock specimen. This implies that discontinuity will weaken the rock. All the rock specimens fail in shear. Referring to specimen 1b, the existing discontinuity cut across the core at about 70°. Thus, the force applied to the rock core is not transmitted uniformly through the core length, resulting in lower UCS value. Nevertheless, there is no discontinuity in specimen 2b, resulting in very high UCS value. The average UCS value by considering the first three limestone rock specimens is 61.74MPa. The detailed reports for each test are attached in Appendix A.
Figure 4.25: Rock Sample for UCS Testing (a) RQ1, (b) RQ2

Figure 4.26: Rock specimen (a) before UCS test, (b) after UCS test.

Table 4.16: Results of UCS of intact rock core specimens.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample</th>
<th>Area (mm²)</th>
<th>Weight (kg)</th>
<th>Dry/Wet</th>
<th>Maximum load (kN)</th>
<th>Maximum Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1a</td>
<td>1963.5</td>
<td>0.535</td>
<td>Dry</td>
<td>123.38</td>
<td>62.84</td>
</tr>
<tr>
<td>2</td>
<td>1b</td>
<td>1963.5</td>
<td>0.54</td>
<td>Dry</td>
<td>111.49</td>
<td>56.79</td>
</tr>
<tr>
<td>3</td>
<td>2a</td>
<td>1963.5</td>
<td>0.53</td>
<td>Dry</td>
<td>128.76</td>
<td>65.58</td>
</tr>
<tr>
<td>4</td>
<td>2b</td>
<td>1963.5</td>
<td>0.53</td>
<td>Dry</td>
<td>194.55</td>
<td>99.08</td>
</tr>
</tbody>
</table>
4.4.2 Rock Input Parameters

After selecting the values for intact UCS, GSI, mi, disturbance factor and intact modulus for the limestone rock slope, the Generalised Hoek Brown Criterion will be presented by the Rocscience RocData software. Mohr Coulomb fit, cohesion and friction angle will be calculated and presented as well. The parameters are tabulated in Table 4.17. Principal stress envelope and shear versus normal stress of limestone is shown in Figure 4.27 and Figure 4.28 respectively.

Table 4.17: Parameters of Limestone Rock Slope

<table>
<thead>
<tr>
<th>Hoek Brown Classification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Intact UCS</td>
<td>56 MPa</td>
</tr>
<tr>
<td>2. GSI</td>
<td>30</td>
</tr>
<tr>
<td>3. mi</td>
<td>10</td>
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<tr>
<td>4. Disturbance factor (D)</td>
<td>0.8</td>
</tr>
<tr>
<td>5. Intact Modulus</td>
<td>12000 MPa</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Hoek Brown Criterion</th>
</tr>
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<tbody>
<tr>
<td>1. mb</td>
</tr>
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<td>2. s</td>
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<tr>
<td>3. a</td>
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</tbody>
</table>

Mohr Coulomb Fit

<table>
<thead>
<tr>
<th>Mohr Coulomb Fit</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cohesion</td>
<td>0.188MPa</td>
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<tr>
<td>2. Friction Angle</td>
<td>30.847°</td>
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</tbody>
</table>

Failure Envelope Range

<table>
<thead>
<tr>
<th>Failure Envelope Range</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Application</td>
<td>Slopes</td>
</tr>
<tr>
<td>2. Sig3max</td>
<td>0.995MPa</td>
</tr>
<tr>
<td>3. Unit Weight</td>
<td>0.026MN/m³</td>
</tr>
<tr>
<td>4. Slope Height</td>
<td>50m</td>
</tr>
</tbody>
</table>
Figure 4.27: Principal stress envelope of limestone.

Figure 4.28: Shear versus normal stress envelope of limestone.
4.5 Rock Slope Kinematic Analysis

Kinematic analysis is conducted to determine the failure modes of the rock slope by referring to the stereonet. There are three types of failure mode: plane sliding, wedge sliding and flexural toppling. The variables that contribute to the probability of failure are slope orientations, friction angle and lateral limits. The critical percentage of rock failure based on different failure modes is summarised in Table 4.18. Since rock slope is heterogeneous, sensitivity analysis was also conducted.

Table 4.18: Critical percentage of failure on different failure modes.

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Critical Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar Sliding</td>
<td>15.40</td>
</tr>
<tr>
<td>Wedge Sliding</td>
<td>7.16</td>
</tr>
<tr>
<td>Flexural Toppling</td>
<td>1.33</td>
</tr>
</tbody>
</table>

4.5.1 Planar Sliding

The stereonet presented in Figure 4.29 is about planar sliding kinematic analysis failure mode in pole vector mode. It is a test for sliding on a single plane. The key elements of the planar sliding kinematic analysis are day lighting condition for planes and pole friction cone where its angle is measured from the center of the stereonet. The great circle of the slope plane is displayed with orientation 40°/175° dip/dip direction. The friction angle of the rock slope is 30°. From Figure 4.29, the region highlighted in red is the critical zone for planar sliding where it is inside the daylight envelope and outside the pole friction cone. Any pole falling within daylight envelope is kinematically free to slide if frictionally unstable. On the other hand, any pole falling outside of the pole friction cone represent planes which dip steeper than the friction angle and can slide if kinematically possible. All poles that are plotted in the region in
red are representing a risk of planar sliding. With respect to all poles, the probability of failure is 3.66% where 254 out of 2933 poles are in the critical region. Contrarily, for the joint set which is circled in red, 252 out of 1636 poles are in the critical region. The risk of the occurrence of planar sliding is about 15.40%. This indicates that a sliding failure along any single joint plane is likely to occur in the dip direction of 175°.

Figure 4.29: Stereonet of planar sliding kinematic analysis.

4.5.2 Wedge Sliding

Figure 4.30 depicts the stereographic projection of wedge sliding kinematic analysis failure mode. Multiple joints can form wedges which can slide along the line of intersection between two planes. The great circle of the slope plane is displayed with orientation 40°/175° dip/dip direction. The friction angle of the rock slope is 30°. The key elements of the wedge sliding kinematic analysis are slope plane, plane friction
cone and intersection plotting. The slope plane defines the day lighting condition for intersections. Any intersection point which plots outside the pit slope great circle satisfies the day lighting condition. The plane friction cone is the angle measured from the equator of the stereonet. The primary critical zone for wedge sliding is the crescent shaped area inside the plane friction cone and outside the slope plane which is highlighted in red. Any intersection points that plot within this zone represent wedges which satisfy frictional and kinematic conditions for sliding. On the other hand, the secondary critical zone, highlighted in yellow in Figure 4.30, is the area between the slope plane and a plane inclined at the friction angle. Wedges do not necessarily slide along the line of intersection of two joint planes. Wedges can slide on a single joint plane, if one plane has a more favourable direction for sliding than the line of intersection. In this case, the second joint plane acts as a release plane rather than a sliding plane. This can occur in either the primary or the secondary critical region. Critical intersections which plot in the secondary critical zones always represent wedges which slide on one joint plane. In this region, the intersections are actually inclined at less than the friction angle; nonetheless, sliding can occur on a single joint plane which has a dip vector greater than the friction angle. Moreover, the intersection contours based on the intersection of all planes are displayed in figure. Since, the contours falls outside the critical zone for wedge sliding, it renders a preliminary indication that wedge sliding is not a problem for this slope orientation. In this rock slope, out of 4299246 intersections, there are 307777 intersections fall into the critical zone. This indicates that wedge sliding is not a great concern for this slope orientation as the critical intersection is merely 7.16%. Figure 4.31 depicts all the plane intersections of the rock slope in the stereonet. From visualization, it can be deduced that the number of critical intersections is relatively small compared to the total number.
Figure 4.30: Stereonet of wedge sliding kinematic analysis.

Figure 4.31: Stereonet of wedge sliding (with all plane intersections in blue).
4.5.3 Flexural Toppling

The stereonet of flexural toppling kinematic analysis is shown in Figure 4.32. The key elements of flexural toppling analysis using pole vectors are slope plane, slip limit plane and lateral limits. The great circle of the slope plane is displayed with orientation 40°/175° dip/dip direction. The friction angle of the rock slope is 30°. Slip limit planes cannot topple if they cannot slide with respect to one another. Goodman states that for slip to occur, the bedding normal must be inclined less steeply than a line inclined at an angle equivalent to the friction angle above the slope. This results in a “slip limit” plane which defines the critical zone for flexural toppling. Slip limit plane is based on slope angle and friction angle. The dip angle of the slip limit plane is derived from the subtraction of slope angle and friction angle which is 45° – 30° = 15°. The dip direction of the slip limit plane is equal to that of the face (175 degrees).

Lateral limits define the lateral extents of the critical zone with respect to the dip direction of the slope. The limit is set at 30 degrees as suggested by Goodman. The critical zone for flexural toppling is the highlighted region between the slip limit plane, stereonet perimeter and the lateral limits. Any poles in this region represent a risk of flexural toppling. From the legend shown in Figure 4.32 there are 39 out of 2933 poles fall into the critical zone which is having a probability of 1.33% for the occurrence of flexural toppling. This statistic shows that the flexural toppling is not a great concern for this slope orientation.
4.5.4 Sensitivity Analysis

Sensitivity analysis is conducted to analyse the effects of slope dip angle, dip direction and friction angle on the critical percentage of each failure mode. The critical percentage of planar sliding, wedge sliding and flexural toppling failure mode is presented and discussed in Section 4.5.1, 4.5.2 and 4.5.3 respectively with the mean of 40° for dip angle, 175° for dip direction and 30° for friction angle. However, changes in those values will alter the critical percentage of the failure modes. Hence, the range of slope dip angle from 20° to 60°, slope dip direction from 155° to 195° and friction angle from 10° to 50° with an interval of 5° are utilised in this analysis.

Figure 4.33 depicts the graphs of critical percentage of planar sliding against the changes in slope dip angle, dip direction and friction angle respectively. The x-axis is presented as percent of range. Since the interval used is five and the difference between
the lower and upper limit is forty, there will be a plot in every 12.5% in x-axis. The critical percentage of planar sliding increases with increasing dip angle. At 70% of range which is a slope dip angle of 48°, the critical percentage of planar sliding has exceeded 20%. This indicates that there will be a 20% or more risk of occurrence of planar sliding. However, dip angle of 30° or less will have zero risk. On the other hand, slope dip direction is not significant in this failure mode. It maintains less than 10% from 155° to 195°. For friction angle, higher slope friction angle will induce safer and stable slope. There is 0% of occurrence of planar sliding if friction angle exceeds 40°. Contrarily, friction angle less than 30° will have a probability of failure at 10% or more.

![Planar Sliding (No Limits): Critical Percentage vs. Percent of Range](image)

Figure 4.33: Kinematic sensitivity analysis for planar sliding failure mode.
Figure 4.34 shows the graphs of critical percentage of wedge sliding against the changes in slope dip angle, dip direction and friction angle respectively. The patterns of the graphs presented are similar to that of the planar sliding kinematic sensitivity analysis. The critical percentage of planar sliding increases with increasing dip angle. At 72% of range which is a slope dip angle of 49°, the critical percentage of wedge sliding has exceeded 20%. This indicates that there will be a 20% or more risk of occurrence of wedge sliding for dip angle of 49°. However, dip angle of 30° or less will have zero chance for the occurrence of planar sliding. On the other hand, slope dip direction is not significant in this failure mode. It remains less than 10% from 155° to 195°. For friction angle, higher slope friction angle will induce safer and stable slope. There is 0% of occurrence of planar sliding if friction angle exceeds 40°. Contrarily, friction angle less than 27° will have a probability of failure at 10% or more.

Figure 4.34: Kinematic sensitivity analysis for wedge sliding failure mode.
Figure 4.35 depicts the graphs of critical percentage of flexural toppling against the changes in slope dip angle, dip direction and friction angle respectively. The critical percentage of planar sliding increases with increasing dip angle. It reaches 2.4% when the dip angle is at the upper limit of 60°. On the other hand, the critical percentage increases when slope dip direction increases, reaching about 1.6% at 195°. For friction angle, higher slope friction angle will induce safer and stable slope. There is 0% of occurrence of flexural toppling when friction angle exceeds 40°. Contrarily, friction angle of 10° (lower limit) has a critical percentage of 2.4%. In short, flexural toppling is not a great concern for this rock slope because the critical percentage of failure is less than 2.5% at the upper limit of slope dip angle and lower limit of friction angle.

Figure 4.35: Kinematic sensitivity analysis for flexural toppling failure mode.
4.6 Rock Slope Stability Analysis

Two cases of rock slope stability analysis were carried out: without anisotropic plane which is a control set and with anisotropic plane. The rock slope stability for both cases were analysed by deterministic method in 3D. Besides, two cut-sections were extracted from 3D rock geometry respectively and analysed 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.

Figure 4.36 depicts the FoS of the 3D rock geometry analysed without anisotropic plane. The least FoS of the entire rock slope is 1.96. This value indicates that the rock slope will be very stable if there is no anisotropic plane. Figure 4.37 shows the FoS of the 2D cross-section (A) at the x-axis of the 3D rock slope which is the global minimum slip surface (maroon) as shown in Figure 4.36. The least FoS analysed by deterministic method is 1.813. On the other hand, the least FOS analysed by probabilistic method is 1.353 with mean FoS of 1.810. The probability of failure (PF) as indicated is 0% with reliability index (RI) more than 1. From Figure 4.39 which also shows the FoS of the 2D cross-section (B) of the 3D rock slope at the x-axis as shown in Figure 4.38, the least deterministic FoS is 1.891 and least probabilistic FoS is 1.398. The mean probabilistic FoS is 1.887. Since the cut section B is not falling in the area of
global minimum, the FoS determined is higher than that at cut section A. The PF is 0% and RI is more than 1 as well.

Figure 4.36: FoS of rock slope without anisotropic plane in 3D. Cut section A is shown.

Figure 4.37: FoS of Cut Section A without anisotropic plane in 2D.
Figure 4.38: FoS of rock slope without anisotropic plane in 3D (control set). Cut Section B is shown.

Figure 4.39: FoS of Cut Section B with anisotropic plane in 2D.
Figure 4.40 illustrates the FoS of the 3D rock geometry analysed with anisotropic plane. The input dip / dip directions are 043°/189 and 0046°/172°. The least deterministic FoS of the entire rock slope obtained is 0.908. This value indicates that the rock slope is unstable and tends to fail at anytime. Figure 4.41 shows the FoS of the 2D cross-section (C) at the x-axis of the 3D rock slope which is the global minimum slip surface (maroon) as depicted in Figure 4.40. The FoS analysed by deterministic method is 0.591. Contrarily, the least FoS analysed by probabilistic method is 0.336. The mean probabilistic FoS is 0.596. The PF as indicated is 100% with reliability index (RI) less than 1. From Figure 4.43 which also shows the FoS of the 2D cross-section (D) of the 3D rock slope at the x-axis as displayed in Figure 4.42, the deterministic FoS is 0.612 and least probabilistic FoS is 0.361 with mean probabilistic FoS of 0.623. Since the cut section D is not falling in the area of global minimum, the FoS determined is higher than that at cut section A. The PF is 100% and RI is less than 1 as well.
Figure 4.40: FoS of rock slope with anisotropic plane in 3D. Cut section C is shown.

Figure 4.41: FoS of Cut Section C with anisotropic plane in 2D.
Figure 4.42: FoS of rock slope with anisotropic plane in 3D. Cut section D is shown.

Figure 4.43: FoS of Cut Section D with anisotropic plane in 2D.
Table 4.19: FoS of with and without anisotropic plane in 3D and 2D analysis.

<table>
<thead>
<tr>
<th>Anisotropic Plane</th>
<th>Least deterministic FoS in 3D analysis</th>
<th>FoS in 2D analysis</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Global Minimum Surface</td>
<td>Non global Minimum Surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deterministic (Least)</td>
<td>Probabilistic Mean</td>
<td>Least</td>
</tr>
<tr>
<td>Without</td>
<td>1.960</td>
<td>1.813</td>
<td>1.810</td>
<td>1.393</td>
</tr>
<tr>
<td>With</td>
<td>0.908</td>
<td>0.591</td>
<td>0.596</td>
<td>0.336</td>
</tr>
</tbody>
</table>

The FoS of rock slope with and without anisotropic plane in 3D and 2D analysis is tabulated in Table 4.19. 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. The difference is because the 3D failure surface does not cross weak rock surface only, but also strong ones, neglecting the over-conservative simplification assumed within the 2D sections. Furthermore, the lower FoS of rock slope with anisotropic plane indicates that the orientations of the joints in the rock slope play an important role in determining the strength of the rock mass. It will contribute to the weakness of the rock mass. The value of orientation is significant and therefore it is a parameter that cannot be ignored when dealing with rock slope stability analysis.
CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Structure from motion (SfM) is a cost and time effective method in the aerial mapping of the slope. Images of the topography were captured by a camera mounted on the UAV. From this study, it is proven that bundle adjustment of images with GCP renders centimeter accuracy result which is a better compared to those without GCP. Hence, the images captured must undergo optimization alignment with the coordinate of GCPs obtained via RTK-GNSS. Capturing images at lower flying height will render better resolution. High accuracy dense point cloud, 3D model, orthophoto and DSM can be produced from the photogrammetric processing with GCP and at lower flying height. Besides, the rock slope data acquisition by UAV mapping improves the quantity and quality of the data obtained compared to scanline survey method since the data of the entire rock slope is obtained. Geological planes extracted from the high accuracy dense point cloud using FACET plugin in CloudCompare is reliable and accurate as it is similar to the data measured manually and within the tolerable limit of 10°. Two major discontinuity sets and random discontinuities were identified from the facets plane extraction. By carrying out kinematic analysis using the orientation data, the rock slope has a higher probability of failure in the planar sliding failure mode (15.40%) compared to wedge sliding (7.16%) and flexural toppling (1.33%). The 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. Besides, the anisotropic plane will weaken the rock
slope strength. In 2D analysis, the critical FoS by probabilistic and deterministic approach for analysis without anisotropic plane is 1.393 and 1.813 respectively. On the other hand, with anisotropic plane taken into consideration, the 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. The objectives of this research are achieved.

5.2 Limitations

This research was planned and conducted strictly from the very beginning to the completion of the research. Nonetheless, there are still some limitations in this research.

- The RTK-GNSS instrument used for measuring the coordinates of the GCP is a single L1 frequency signal receiver which can only minimize the RMSE to tenth centimeter. To achieve a lesser RMSE to decimate error, dual frequency signal receiver, L1 + L2 should be utilized. However, due to the cost of the dual frequency signal receiver instrument is extremely high, L1 frequency receiver RTK-GNSS instrument was applied in this study.

- Photogrammetry approach by UAV is using the overlapping of 2D images to extract the sparse clouds by detecting the same features appearing in multiple images. The model produced is digital surface model (DSM) instead of digital elevation model (DEM). Hence, the rock outcrop which is covered with vegetation is unable to be mapped and analysed digitally in the software.

- Due to the limitation of the current version of Rocscience Slide3 software where it analyse the 3D rock slope in limit equilibrium method, the software can only perform analysis in deterministic approach.
5.3 Recommendations

A few recommendations and suggestions were suggested based on the results and discussions throughout the research.

- A dual frequency RTK-GNSS instrument can be utilized to carry out the coordinates measurement if decimate accuracy is necessary.
- Terrestrial laser scanner (TLS) should be used for capturing the rock outcrop covered with vegetation since it can penetrate through the vegetation and detect the points of the rock.
- The time used for the acquisition of the coordinate of one GCP can be longer so that the data received is more stable.
- The rock slope stability can be analysed using finite element modeling (FEM).
- The 3D rock slope geometry can be analysed using probabilistic approach when the software launches the features.
- Back analysis can be carried out on the rock surface where it has failed to determine the factor of safety of the rock slope failure surface.
REFERENCES

ASTM D7012-14 (2008), Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures


Greif, V. and Vlcko, J. (2017), Kinematic Analysis of a Rock Slope at Strecno Castle (Slovakia) Based on the Processing of the Point Cloud Generated by UAV Photogrammetry BT - Advancing Culture of Living with Landslides, WLF 2017: Advancing Culture of Living with Landslides, pp. 419-429.


Janbu N. (1973), Slope Stability Computations in Embankment Dam Engineering, John Wiley and Sons Ltd., New York.


APPENDIX A:

UCS TEST RESULT
### Uniaxial Compressive Strength of Intact Rock Core Specimens

**Sample Name/rock type:** LIMESTONE  
**Sample no:** 1a  
**Client:** ASSC. PROF. DR. MOHD ASHRAF MOHAMAD ISMAIL  
**Location:** UiTM, PENANG  
**Lab name:** GEOLOGY LAB.

<table>
<thead>
<tr>
<th>Sample measurement</th>
<th>Test result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, mm</td>
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<tr>
<td>Height, mm</td>
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</tr>
<tr>
<td>Weight, kg</td>
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<tr>
<td>Area, mm²</td>
<td>1963.5</td>
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</tbody>
</table>

*The test data given herein pertain to the sample provided only. This report constitutes a testing service only. Interpretation of the data given here may be provided upon request.*

**TESTED BY:** Roseffendy bin Ramlan  
**DATE:** 23/3/2018  
**CHECKED BY:** Mohd Khairul Azhar bin Ismail  
**DATE:** 23/3/2018
**Uniaxial Compressive Strength of Intact Rock Core Specimens**

<table>
<thead>
<tr>
<th>Sample measurement</th>
<th>Test result</th>
</tr>
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<tbody>
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*The test data given herein pertain to the sample provided only. This report constitutes a testing service only. Interpretation of the data given here may be provided upon request.*

**Sample Name/rock type:** LIMESTONE  
**Sample no:** 1b  
**Client:** ASSC. PROF. DR. MOHD ASHRAF MOHAMAD ISMAIL  
**Location:** UiTM, PENANG  
**Lab name:** GEOLOGY LAB.

**Reference**  
ASTM D7012-14 Method C

**Tested by:**  
Roseffendy bin Ramlan  
**Date:** 23/3/2018

**Checked by:**  
Mohd Khairul Azhar bin Ismail  
**Date:** 23/3/2018
# Uniaxial Compressive Strength of Intact Rock Core Specimens

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<th>Sample measurement</th>
<th>Test result</th>
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**Sample Name/rock type:** LIMESTONE  
**Sample no:** 2a  
**Client:** ASSC. PROF. DR. MOHD ASHRAF MOHAMAD ISMAIL  
**Location:** UiTM, PENANG  
**Lab name:** GEOLOGY LAB.

**Sample measurement**  
**Test result**

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<th>Diameter, mm</th>
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**DATE:** 23/3/2018
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<thead>
<tr>
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</tr>
<tr>
<td>Area, mm²</td>
<td>Dry/wet</td>
</tr>
<tr>
<td>1963.5</td>
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