A NOVEL METHOD FOR MEASUREMENT OF ORIENTATION OF ROCK JOINTS FROM POINT CLOUD BY FACET AMALGAMATION APPROACH

Anthony C.T. So, W.K. Leung and Jeffrey C.F. Wong
Geotechnical Engineering Office,
Civil Engineering and Development Department, the Government of the Hong Kong Special Administrative Region
101 Princess Margaret Road, Homantin, Kowloon, Hong Kong
E-mail: actso@cedd.gov.hk

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ABSTRACT: The Geotechnical Engineering Office (GEO) of Civil Engineering and Development Department (CEDD) of the Government of the Hong Kong Special Administrative Region has been employing various remote sensing methods to enhance the engineering geological input in supporting geotechnical studies. For slope mapping, the use of conventional manual mapping method to measure joint orientations (i.e. dip angles and dip directions) has been found to be expensive, time-consuming and environmentally unfriendly. In addition, there may be constraints to access to remote sites and mapping of rock slope on site may pose safety hazards to the field personnel. To improve effectiveness and efficiency, many studies have been carried out to reduce the amount of field work by remote sensing techniques, and the focus was mainly on computer-aid generation of individual joint planes from point cloud captured either by laser scanning or photogrammetry. In view that such an approach often requires good understandings of the conditions of rock joints such as variations in orientations in different parts of a joint planes due to waviness and unevenness. To this end, delineation of joint plane requires setting of parameters by a trial and error approach which is not technically desirable. To overcome this problem, we have developed a new approach which is entirely different from the aforementioned computer-aid approach. Instead of attempting to form joint planes from point cloud, we first used point cloud to generate a 3-D triangular mesh to model the slope face. By measuring the dips and dip directions of all triangles (facets) of the mesh, a stereoplot of all facets was generated. Statistically, the majority of facets should be able to represent the overall orientations of all measurable discontinuities on the slope, and the facets due to waviness and unevenness in random directions should be in minority. To this end, by amalgamation of the orientations of facets, the major joint sets of the slope could be analysed. An assessment of different algorithms using K-d Tree, Fast Marching and this new approach have been performed. The results show that this novel method is more effective and efficient in identifying rock joints as compared to other algorithms with less requirements and more tolerance in parameter setting. This new approach has been proven to be an easy-to-use and user-friendly method which can greatly facilitate rock slope stability analysis.

1. INTRODUCTION

Over 60% of the land area in Hong Kong (1,100 km^2) is hilly terrain. Constrained by the rugged topography, only 25% of Hong Kong's land area has been built-up to support the livelihood of the 7.5-million population. In addition to using reclamation to expand our urban areas, our urban fringe is also extending by cutting into the hillside to create more useable land. Large number of site formation works have therefore created many cut slopes fringing the flat land so created. To date, there are over 60,000 registered man-made slopes in the Catalogue of Slope which is maintained by the GEO of the CEDD of the Hong Kong Special Administrative Region Government. These man-made slopes are generally categorised into cut, fill and retaining wall features. The presence of these slope features without proper stabilisation works and maintenance may pose hazards to the public. Amongst the slope features, those cut slopes which were formed by cutting into hillside are outcropped by soil and/or rock materials, and stabilisation works for soil and rock slopes are different. For soil slopes, soil mass is mainly stabilised by soil nailing comprising steel bars and cement grout with engineering design. For rock slopes, with the presence of discontinuities in rock mass, the failure modes are mainly associated with the orientations of individual joints and joint intersections. Given this location-specific failure mode, stabilisation works and maintenance of rock slopes require more intensive fieldwork and measurements by engineering geological practitioners on site.

Conventional method to carry out assessment of stability of rock slopes is to map the rock slopes manually by experienced geologists. Hoek and Bray (1981) and Duncan & Christopher (2004) provided useful guidances for analysing of rock slopes and have widely been used. Since manual field mapping often requires erection of scaffolding and vegetation clearance, and the cost and time involved are substantial. In addition, mapping of rock slopes on site may pose safety hazards to the field personnel. In view of these, remote sensing is considered as a useful means to support study of rock slopes.

2. CURRENT APPROACHES GENERALLY ADOPTED

Using different remote sensing techniques, especially LiDAR survey, for mapping rock slopes has been evaluated in various studies (Brugger et al., 2019; Gigli & Casagli, 2011; Slob, 2010; Lato et al., 2009; Lato & Vöge, 2012; Vöge et al., 2013 and Wong et al., 2019). Positive feedbacks have been experienced by using point-cloud models of rock slope surface generated by the LiDAR technology and photogrammetry supported by terrain modelling software packages for mapping and interpretation of the orientations of rock joints.

Two main approaches are commonly adopted by commercial or open source algorithms in the market to identify rock joints from point cloud datasets. The first approach (Approach A) utilizes 3D surface reconstruction with mesh generation as presented in Figure 1, while the other approach (Approach B) employs point cloud segmentation without mesh generation (Figure 2). In Approach A, after forming meshes from the point cloud data, adjacent meshes that are sufficiently planar and that fulfil the input settings will be included as potential joint surface. The final step is the clustering process, in which joints of similar orientation are grouped into a joint set. Formation of meshes is not required for Approach B, in which the process starts from a randomly picked seed point. Most algorithms of Approach B divide the point clouds into sub-cells, then compute elementary planar objects and aggregate them progressively according to a planarity threshold.

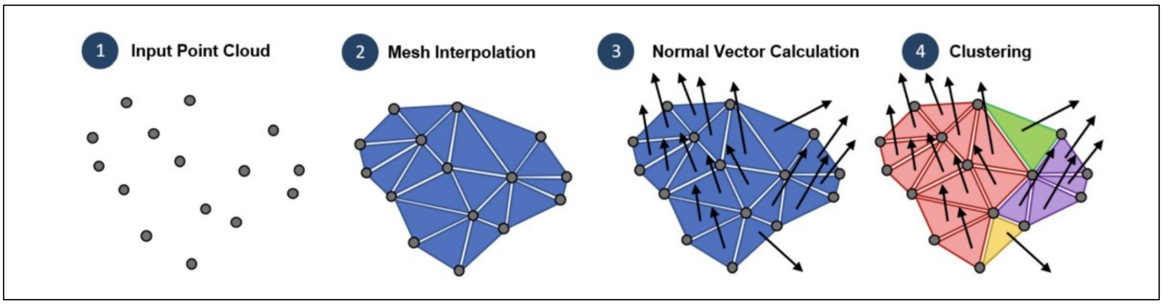


Figure 1: Approach A - 3D surface reconstruction with mesh generation (for example, PlaneDetect (Voge et al., 2013), Split-FX (Split Engineering, 2010))

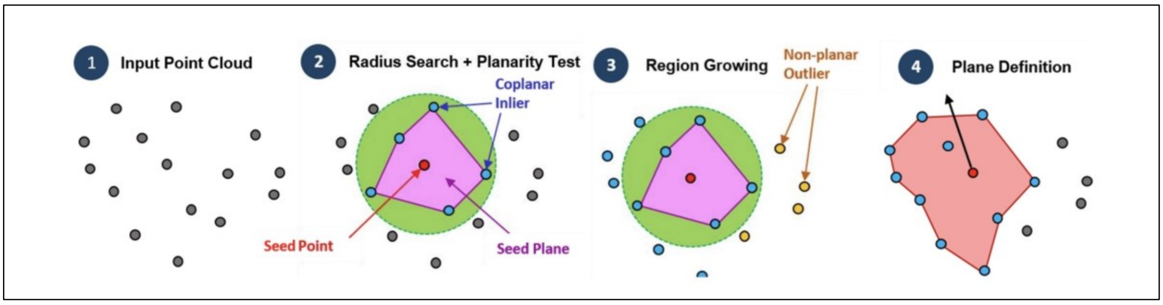


Figure 2: Approach B - Point cloud segmentation without mesh generation (for example, CloudCompare (Dewez et al., 2016), Discontinuity Set Extractor (DSE) (Riquelme et al., 2014))

2.1 Limitations of Existing Approaches

- There are quite a large number of parameters to be set in order to optimize the delineation results, for example, the search radius, the distance and angle threshold for least-square fitting, the maximum edge length of each facet, the minimum number of points per facet, etc.
- The optimum parameters have to be determined by trial-and-error approach, which is not technically desirable and is time-consuming. It would also be difficult to assess which parameters are more crucial. Moreover, the optimum parameters would vary among slopes with different joint patterns and slope geometry.
- "One-set-of-parameters-fits-all" execution of rock joint identification is not practicable for mapping of individual joints due to their heterogeneous nature.
- Large variations in the total number of joints identified are expected with varying input parameters including different algorithms/approaches adopted and difference in plane size/point count threshold adopted in defining a joint plane.
- Variations in curvature/waviness exceeding the threshold of a single joint plane would result in segregation of sizeable joint planes into several smaller planes.

3. NEW FACET AMALGAMATION APPROACH

3.1 General Principle

As the existing approaches have their limitations and are not entirely suitable for rock slope study, especially in Hong Kong conditions, a new facet amalgamation approach (FAA) is proposed in this study and is illustrated in Figures 3 & 4. Unlike other methods, this new novel method does not attempt to identify individual rock joints from the point clouds in the first step. Instead, we make use of the point cloud to form a triangular 3-D mesh containing numerous of vertex. Since the vertices of the triangles (facets) contain coordinates and heights (x,y,z), using these vertices to calculate the orientation of a particular facet in the mesh so generated will give dip and dip direction of this facet (Figure 3).

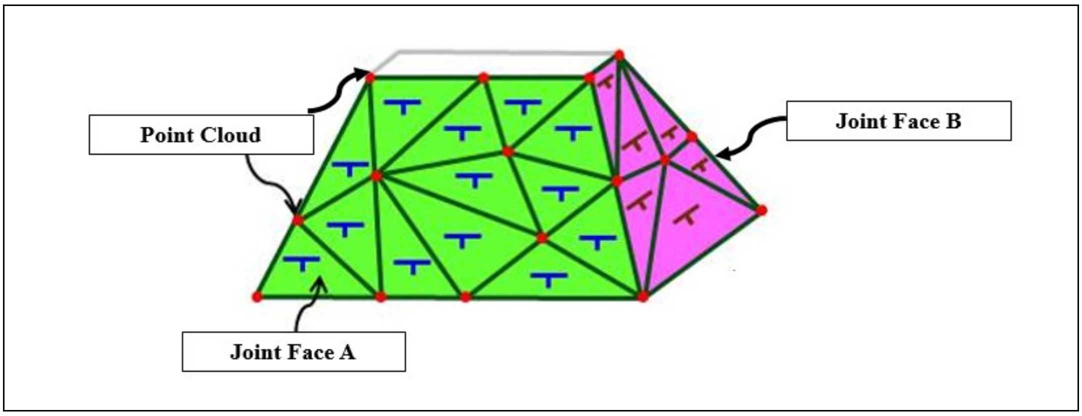


Figure 3: Principle of Facet Amalgamation Approach

Rock joints are generally planar structure and therefore facets on a specific rock joint will more or less have similar dips and dip directions (Figure 3). Following this logic, when we measure dips and dip directions of all the facets generated from the point clouds, it should give the general dips and dip directions of the rock joints on a specific rock face (Figure 4).

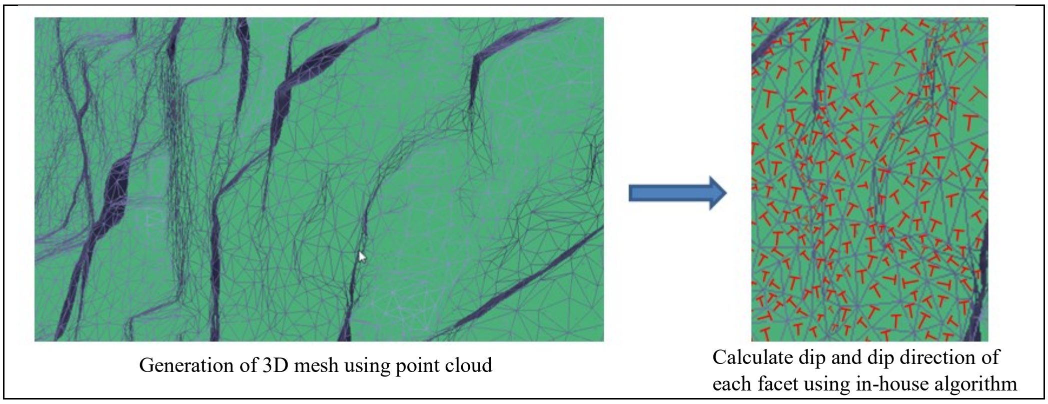


Figure 4: Dips and Dip Directions of Facets on a Rock Slope

Although there may be other surfaces such as human induced fractures and broken edges which may generate "Noise" and influence the results. Such a 'Noise' is considered random in nature and can be eliminated when a large number of measurements of facets representing rock joints are collected, and will not affect the entire process. In this study, we regard dips and dip directions of rock joints are consistent 'Signal' and the Signal-to-Noise will become larger when more data are collected.

After collection of a huge number of dips and dip directions of the facets, we can input the readings onto the stereonet to form a stereoplot of all the facets of the entire rock slope, similar to the conventional method for rock slope study. As discussed above, the joint orientations are the "Signal" and should occupy the majority parts of the stereoplot. The rock joints will concentrate in a particular area and major joint sets can then be identified by contouring. Other features like broken edges and fractures will distribute randomly in the stereoplot and will not form major joint sets (Figure 5).

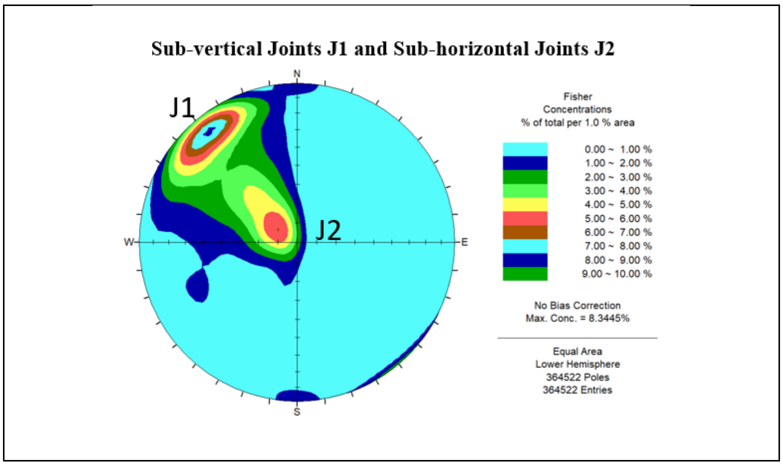
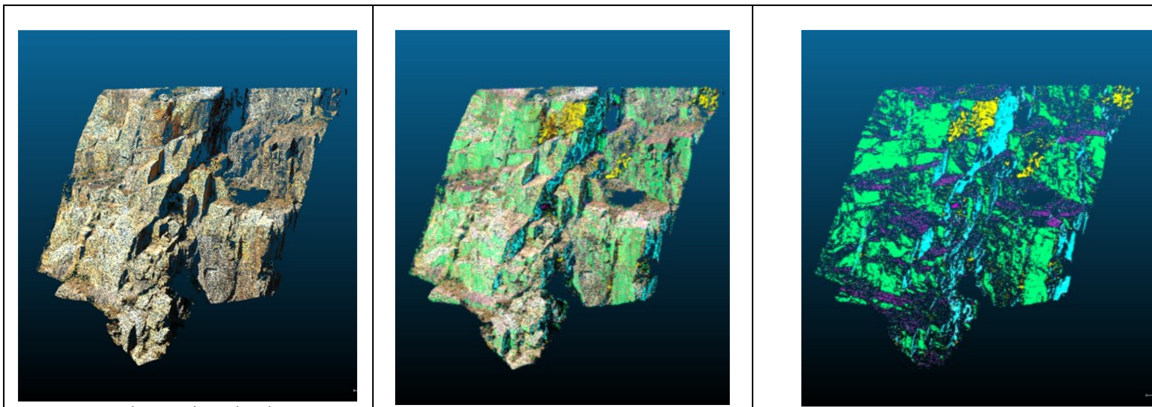


Figure 5: Example of a Stereoplot of All Facets of a Rock Slope

After the centers of the major joints sets are identified by contouring, it is necessary to determine the locations of individual joint sets in the mesh model. As discussed above, facets on a specific joint plane should have similar dips and dip directions irrespective of size of facet. To filter out the facets which belong to the particular major joint set, it is necessary to set intersecting envelop of each major joint set in the stereoplot. It is considered that the facets within the same joint set will fall within the envelope of this joint set. To identify these major joint sets, we have developed an algorithm to filter out facets which belong to the same joint set by this intersecting envelope method. After the respective facets are identified, the facets belonging to the same facet are then 'amalgamated' to form a single rock joint. By superimposing the amalgamated facets onto the images or colour point clouds, the results can then be verified (Figure 6).



Colour Point Cloud | Colour Point Cloud and the Major Joint Planes Identified Using FAA | Major Joint Planes Identified Using FAA

Figure 6: Major Joint Planes Identified Using FAA

3.2 Assumptions of FAA

As can be seen above, this new FAA has successfully identified major joint sets of a rock slope. To ensure that the FAA can be carried out smoothly, a number of assumptions need to be considered, which are : i) each facet is formed by three points; ii) facets on a specific joint plane should have similar dips and dip directions irrespective of sizes of facets; iii) stereoplots of all facets should give general orientations of major joint sets; iv) size of joint plane and persistence will affect the number of readings; v) vegetation and artificial objects shall be removed prior to measurements and vi) random noise along edges and artificial fractures is expected but should not affect the overall results.

3.3 General Workflow

The general workflow of the FAA is given in Figure 7.

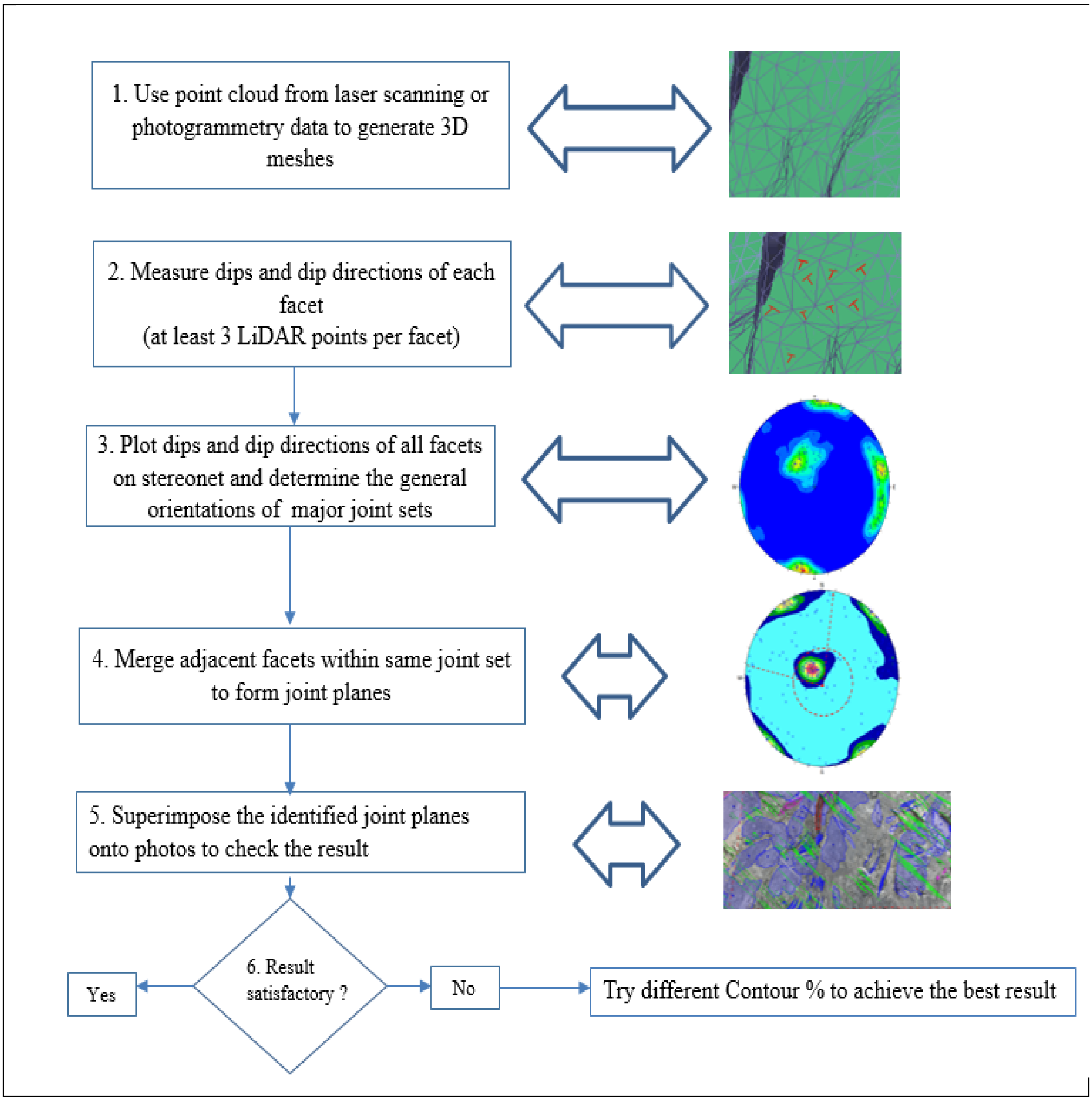


Figure 7: Workflow for Identification of Rock Joints Using FAA

3.4 Evaluation of Results

In order to assess the effectiveness and reliability of the new FAA, an evaluation which included comparison of the number of rock joints was conducted. A portion of rock slope no. 11NW-D/C80 in Homantin, Hong Kong was selected as the study area and the terrestrial LiDAR data collected were used (Figure 8).

Rock joint identification for the study slope using Kd–Tree and Fast Marching approaches of CloudCompare, and the newly developed FAA were carried out. In the FAA approach, the only parameters needed to be set are the envelopes of each major joint sets and it was found that the results are not very sensitive to the parameters setting (Figure 8). It was also found that minor variations of the size of envelops in FAA does not significantly affect the identification of rock joints. However, the parameter settings in other methods such as the Kd-Tree and Fast Matching approaches are very important and only little tolerance is allowed. Failure to use suitable parameters in such methods will result in undesirable results (Figure 8).

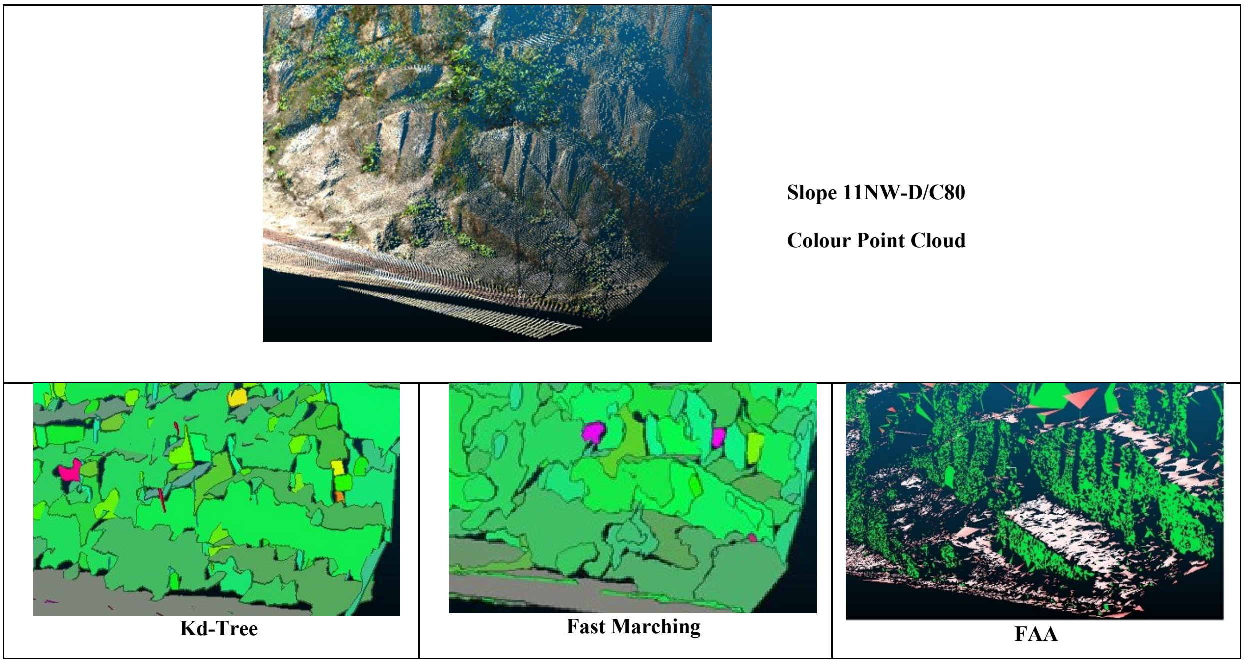


Figure 8: Comparison of Results Using Various Approaches

3.5 Factors Affecting the Results

Although the FAA has been proven to be effective in identification of rock joints, there are a number of factors which will affect the results.

Different Remote Sensing Techniques: Line-of-sight (LOS) problems were found in terrestrial laser scanning (TLS), handheld laser scanning (HLS) and terrestrial photography in which sub-horizontal joints may not be completely measured at the survey point or traverse of field operation. Drone or airborne LiDAR or photography are recommended for future survey to obtain a complete dataset. In addition, more noise was found in HLS than other laser scanner and the facets may contain significant errors. Higher quality laser scanner is recommended to achieve better results.

Vegetation Cover – Green Filter and CSF: Many rock slopes are partly covered by vegetation and therefore it will affect the results when using the FAA. The vegetation cover can be generally removed by manual trimming of the point cloud. In order to effectively and efficiently perform this operation, we have developed a Green Filter to remove the green vegetation from the point cloud (Figure 9). In addition, Cloth Simulation Filtering (CSF) method can be used to further remove other above ground features (Zhang et al., 2016) (Figure 10). With these two algorithms, the vegetation cover and other above ground features can largely be removed for accurate identification of rock joints.

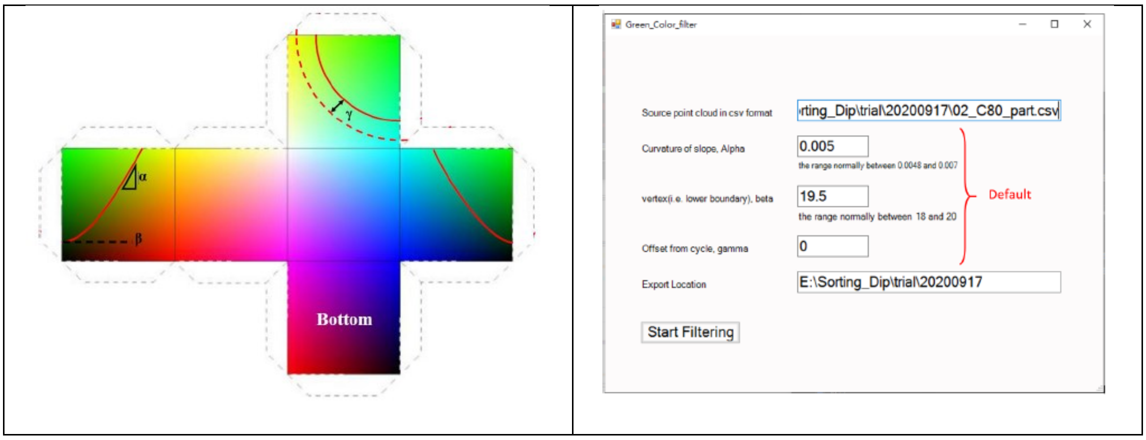


Figure 9: Green Filter to Remove Vegetation on Rock Slopes

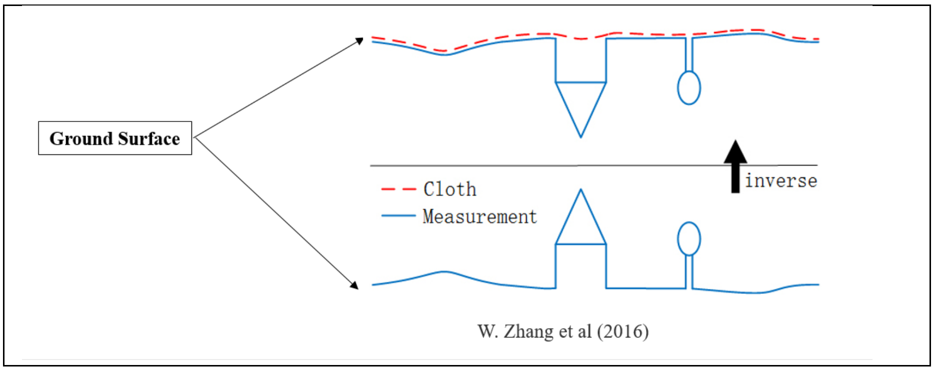


Figure 10: Removal of above Ground Features Using CSF (Zhang et al., 2016)

3.6 Setting of Intersecting Envelops

To set the intersecting envelopes for identification of major joint sets, inputs from engineering geologists are required for this important step. In order to obtain a better understanding of the general joint patterns, a site walkover prior to the survey to sense the general orientations of joint sets is recommended. The visit can help setting the intersecting envelopes of each major joint set. Since there may be major joint sets or geological features such as faults which occur less frequently than other joint sets in a particular rock joints, the number of facets of these less frequent joints will be less and these joints may not be easily picked up in the stereoplots. To overcome this problem, it is recommended to filter out the rock joints with high occurrence first so that less common but important joints and geological structures can be identified. Furthermore, rock joint orientations in different structural domains may be various. It is also recommended that identification of rock joint using FAA should be carried out in each structural domain in order to avoid mis-identification of rock joints.

4. POTENTIAL APPLICATIONS

4.1 Geotechnical Applications

Slope Stability Analysis: Having identified all major joint sets, the next step of the rock slope study is to carry out a stability analysis. By using the FAA, we have also satisfactorily identified the major unstable joint planes in the study area.

By using the conventional rock slope stability analysis method, we can work out the failure envelopes of a given rock slope after measuring the trend and slope angle of this slope. In the FAA, we consider when the poles of any facet falls within these unstable zones, the corresponding facets will be unstable. By plotting all the facets on this stereonet, we should be able to find out the facets which fall within these zones. By amalgamating these facets, we can identify and locate the unstable rock joints (Figures 11 and 12).

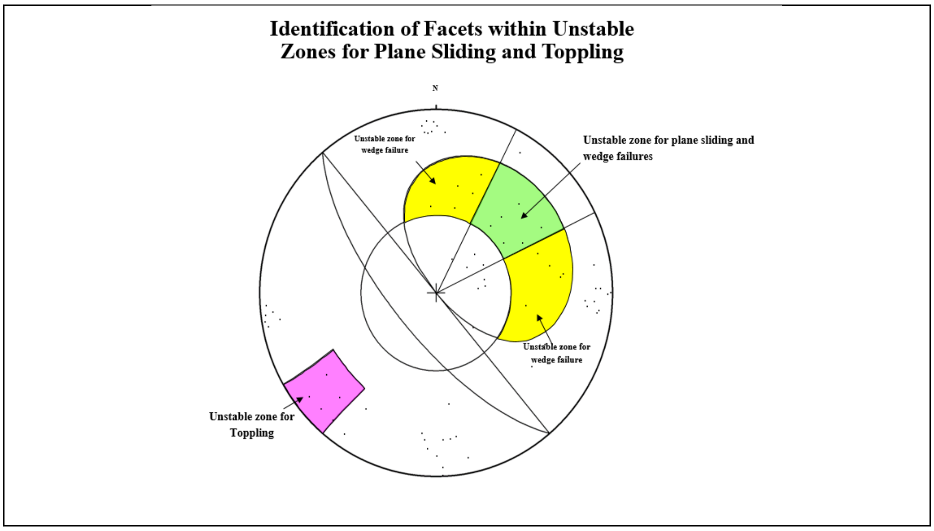
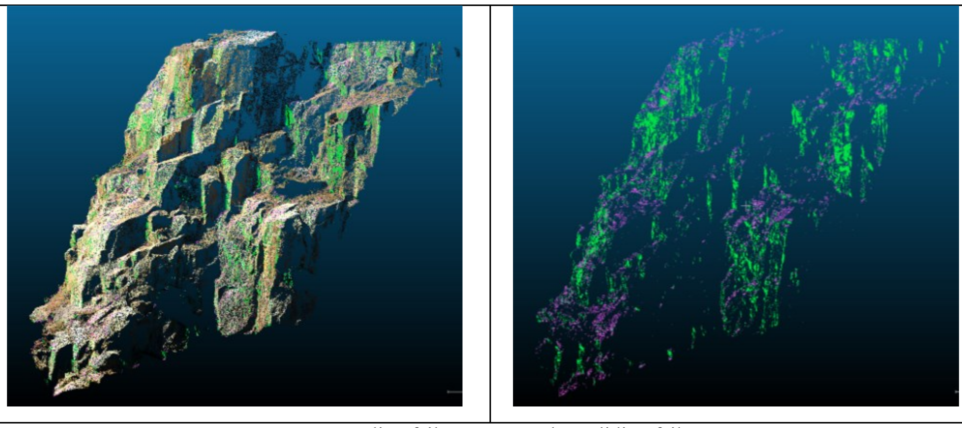


Figure 11: Slope Stability Assessment Using FAA



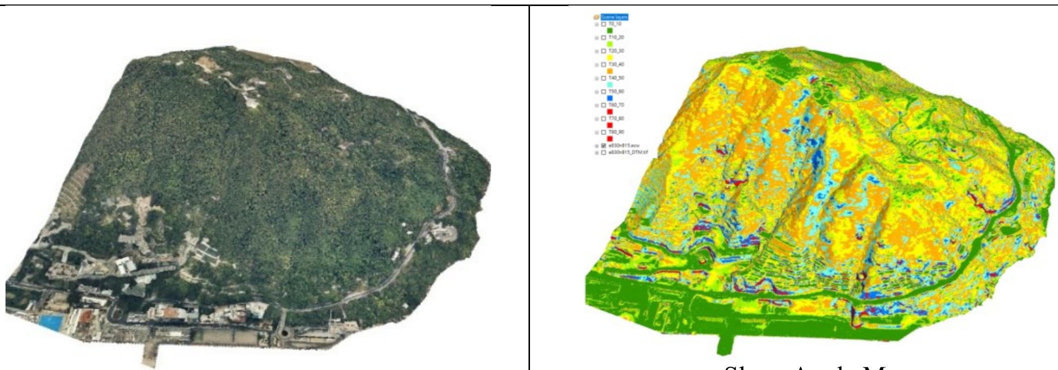
Green – Toppling failure   Purple – Sliding failure

Figure 12: Result of Slope Stability Assessment Using FAA

Other Geotechnical Applications: The FAA can also be able to identify some hidden cut and fill terraces on the hillside. There were numerous cut and fill platforms in Hong Kong such as squatters and agriculture terraces formed in the past. These small terraces are now concealed by dense vegetation and pose many potential geotechnical hazards. These old cut and fill terraces tend to form a series of continuous discernable lines of similar elevations. By using the FAA, we could identify facets of the flat terrace areas within hillside by setting a specific slope angle (Figure 13). Following the same approach, we can extend this to generate a slope angle map by setting different slope angles (Figure 14).

(Source: https://gwulo.com)
Terraces above Tai Hang Road (1969)   Vegetated Slopes   Amalgamating 0-10 degrees Facets

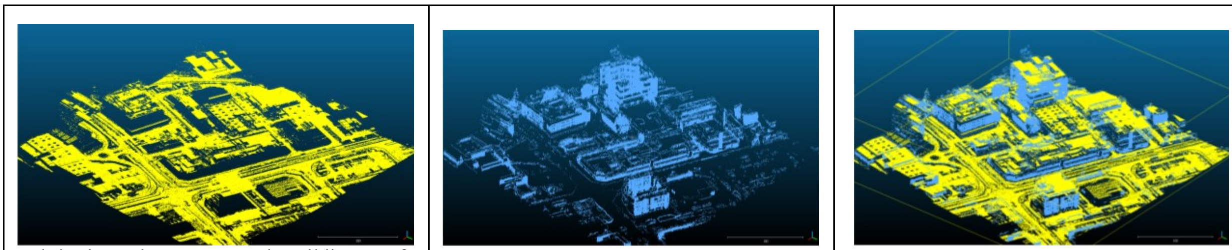
Figure 13: Terraces Identified by FAA



Mt Davis   Slope Angle Map

Figure 14: Generation of Slope Angle Map Using FAA

Apart from geotechnical applications, the FAA can have other potential non-geotechnical applications. We can use the FAA to identify building footprints since the walls are mostly vertical and roofs are flat. By setting different angles, the facets of the vertical walls and horizontal roofs can be extracted and these features can be converted a BIM compatible format (Figure 15). Furthermore, the FAA can be used for checking compliance of products such as roof flatness, verticality of walls & panels. With point clouds obtained from different times, we could detect the tilting range of structures. We can also use this method for quality check of works such as defects, flatness and local anomalies.



Sub-horizontal Facets – Road, Building Roofs | Sub-vertical Facets – Building Walls | Sub-horizontal and Sub-vertical Facets

Figure 15: Identification of Buildings and Roads Using FAA

5. FURTHER WORKS

5.1 Full Automation

At this moment, the FFA is a semi-automatic operation for identification of rock joints requiring inputs from engineering geologists. Further development to convert of this approach to a fully automatic method is possible. A deep learning algorithm may be employed later to increase the effectiveness and efficiency of this approach.

5.2 Stability Analysis

Although the FAA can identify major unstable joints which are subjected to sliding and toppling failures, we are still fine-tuning the algorithm to identify rock joint intersections which can result in wedge failure. The wedge failure involves spatial relationships between adjacent joint planes and the task for identifying these features are very challenging.

5.3 Combination of FAA with Other Remote Sensing Techniques

This approach can rapidly identify orientations of rock joints which are the most critical elements in rock slope stability analysis. Other parameters such as infilling, joint aperture, roughness, seepage are still required for a complete analysis. The FAA can have the potential to combine with other remote sensing techniques, in particular infrared thermography to identify seepage, soil seams and fractures to provide a completed set of geotechnical information for slope stability analysis.

6. CONCLUSIONS

Joint orientations are the most critical element to rock slope stability analysis. Rock slope mapping using computational conventional manual mapping method to measure joint orientation (i.e. dip angles and dip directions) has been found to be expensive, time-consuming and environmentally unfriendly. In this study, we have successfully developed a novel approach that can rapidly and accurately identify major joint sets as compared to other approaches. An assessment of different algorithms and this new approach have been performed. The results show that this novel method is more effective and efficient in identifying rock joints as compared to other algorithms, with less requirements and tolerance for parameter setting. This approach has proven be an easy-to-use and user-friendly method which can greatly facilitate rock slope stability analysis.

7. ACKNOWLEDGEMENTS

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