3D Modeling Using LiDAR Data and its Geological and Geotechnical Applications

Hui Hu[*], Tomas M. Fernandez-Steeger, Mei Dong, Hieu Trung Nguyen, Rafig Azzam
Department of Engineering Geology and Hydrogeology
RWTH Aachen University
Aachen, Germany
[*]Corresponding author: hu@lih.rwth-aachen.de

***Abstract*—3D Terrestrial Laser Scanning (TLS) facilitates survey campaign which is essential step for point cloud data acquisition and further research. IRIS-3D, one typical media of TLS, has been widely applied to comprehensive fields such as commercial survey, engineering, mining and industrial markets. The process of three dimensional surface modeling (3DSM) was elaborated and quantification for different investigative object was illustrated through three case studies. The resolution of laser scanning is various according to the nature variability of object and requirement of further application. Comparison of volume results computed on two platforms of PolyWorks and GOCAD was conducted in case of volume calculation which needs low resolution. Landslide stability was analyzed by using both Limit Equilibrium Method (LEM) and Finite Element Method (FEM) platforms which need profiles or elevation contours generated by 3DSM. This case needs medium resolution. Joint analysis as the third case which needs high resolution was also quantitatively discussed. Three different applications demonstrate visible and potential benefits TLS offers both in geological engineering and geotechnical fields.**

Keywords-terristrial laser scanning; joint analysis; landslide stability analysis; volume calculation; FEM; LiDAR

I. INTRODUCTION

3D TLS (terrestrial laser scanning) technique has enhanced the conventional survey into a more modern and convenient way. The main advantages are high point density, high spatial resolution, accuracy of acquired data sets, as well as easy use for engineers and researchers. TLS-based survey generates 3D surface data with local coordinate system as a so called "point cloud". Sole point datum contains the spot position with *–xyz* coordinates where single laser beam touches the object. Data acquisition in virtue of scanning of laser beam complies with line by line and from bottom to top so that moving objects between scanner and object of interest produce only fragments in the scan data. The deployment of the laser scanner plays an important role in data acquisition process. Appropriate deployment can save time and station change is essential to generate data of high quality. Furthermore, it helps to facilitate post-processing of the data.

[*]Sponsored by China Scholarship Council (2008640010)

On the market are TLS systems from many manufactures available e.g. ILRIS-3D, Mensi GS2000, Riegl LMS Z210, Leica Cyrax HDS3000. All of them have their individual strength and disadvantages depending on the desired application. Therefore no one system is dominant which covers all applications. We have been using ILRIS 3D system to acquire data for many geological and geotechnical applications (Fig. 1). Three of them are described in detail in the case study part. The reason for choosing TLS surveys is that an accurate and higher density dataset can be created with more than 95% time savings (according to the civil engineering field notes done by Florida Department of Transportation, Tab. 1).

Figure 1. ILRIS 3D TLS in field.

TABLE I. COMPARISON OF TRADITIONAL SURVEY AND ILRIS 3D

	Traditional Method	**ILRIS-3D**
Setup Time	16 hours	5 minutes
Min. # People Required	2	1
Total Labor Time	32 hours	5 minutes
Data Collection Time	1 minute	15 minutes (total)
Min. # People Required	1	1
Total Time	1 minute	15 minutes
Total Data Processing Time	<5 minutes	30 minutes
Total # of Measurements	<500	>1,000,000
Time to Completion	~32 hours	~50 minutes
Time per Measurement	230 seconds	0.003 seconds
Final Data Output	Numeric Comparison	3D structural visualization

There are two main focuses in research which are processing of point cloud data and application of LiDAR (Light Detect and Ranging) technology. To the first research field belong various efforts, developing a new low-cost color laser scanning [1]; developing an efficient algorithm for simultaneous reconstruction and segmentation of surfaces and proposing a new algorithm for merging ground-based and airborne meshes [2]; object identification in LiDAR data with artificial noise [3]; employing 3D line features for point clouds registration [4]. Moreover, the direct geo-referencing technique which is suitable for TLS and airborne LiDAR systems has been extended to stationary LiDAR system [5]. On the other hand, the domain of LiDAR tech application has been broader and broader involving 3D stratigraphic modeling for improving reservoir model and constraining forward seismic model [6]; landslide inventories creating especially under steep and rocky region [7]; structural evaluation of discontinuities in rock masses [8]; geometric tolerances analysis of tunnel structures [9]; changing detection of landslide [10], 3D modeling of landslide in open pit [11] and rock-fall hazard assessment [12].

It is obvious that a real 3D surface model (3DSM) is the key for further application and analysis. This paper aims to present a detailed workflow to construct a 3DSM of high accuracy from LiDAR-derived spatial data, as well as apply it to problems of geological and geotechnical engineering. A good combination of careful pre-processing of field scan data in PolyWorks and sophisticated 3D surface modeling is the kernel of this workflow (Fig. 2). Three 3DSM-based case studies, i.e. volume calculation, slope stability analysis and joint analysis, are described to demonstrate the applicability of this proposed workflow. The primary objective of 3D surface modeling on a quarry area is to precisely reconstruct surface relief for volume calculation and whereupon rigorously extract cross section for slope stability analysis. In addition, using GOCAD with better technique for sealing of covering plane to 3DSM facilitates and optimizes volume calculation. Joint analyzing enunciates that discontinuity of high resolution can be characterized along large slope.

II. 3D Surface Modeling

For a TLS project besides the deployment, the number of stations, line of sight, distance to object and campaign season should be taken into account. The season of leaf-off is the best time for field scanning. Due to the scanner's limited view field (40°*40°) the stations for scanning should be selected carefully to minimize the number of stations or scans and to prove a good overlap of the scans for the later merging.

The developed methodology in this paper uses two steps of processing to integrate LiDAR surface data into 3D geological models that can be used for 3D geotechnical modeling. The first step is processing in PolyWorks, and the second one is in GOCAD (Fig. 2).

Firstly raw point cloud data have to be converted using the ILRIS-3D Parser, to convert the data into PIF (Program Information Files) format of 24-bit texture which is then imported into PolyWorks. Secondly preparatory work, like

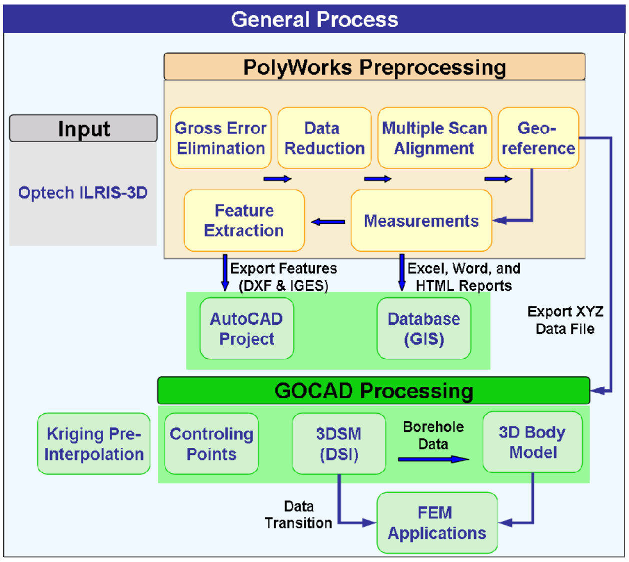

Figure 2. Workflow of general 3DSM construction for applications.

gross error elimination, data reduction and multiple scan alignment has to be done before georeferencing. Especially error elimination and redundant data reduction are important tasks to enhance the data processing due to the large amount of data in larger scan projects and constraint of computer performance. Noise (i.e. data in front and behind the object of interest and irrelevant data) reduction should be done at the beginning of the processing to reduce the number of data. Data cleaning may also be performed after the scan alignment, but only if the scan data are not too large. After this data cleaning step the scans can be merged in the alignment process which is done with the PolyWorks module Align. Precise work in this step is essential to keep accuracy of high level. As the alignment tries to perform a data merge with a low gross error, errors are spatially distributed. This may lead in case of a bad alignment that all data objects migrate. The final step is the geo-referencing of the point cloud data to generate a consistent 3D model. Polyworks also offers the option to transform the point data into a vector surface model. Actually for both geological and geotechnical modeling many scientists prefer to set up their 3DSM in a geological 3D modeling program such as GOCAD.

As GOCAD accepts –*xyz* coordinates data, the data are exported in this file format from PolyWorks. To efficiently interpolate 3DSM from point data, geostatistical methods is usually applied. In our investigations, the Kriging algorithm is the most effective means according to work progress and quality of the model derived. TXT file with –*xyz* coordinates can be directly imported to GOCAD. Kriging interpolation with normal density of cell size of 50cm*50cm makes rambling data points (e.g. shadow area occurring due to noise reduction and no reflection from water area is given in A of Fig. 3) regularly distributed. The construction of 3DSM has been performed in GOCAD with the DSI algorithm (Discrete Smooth Interpolation). The visualizations after Kriging interpolation and DSI are respectively shown in B and C of Fig. 3.

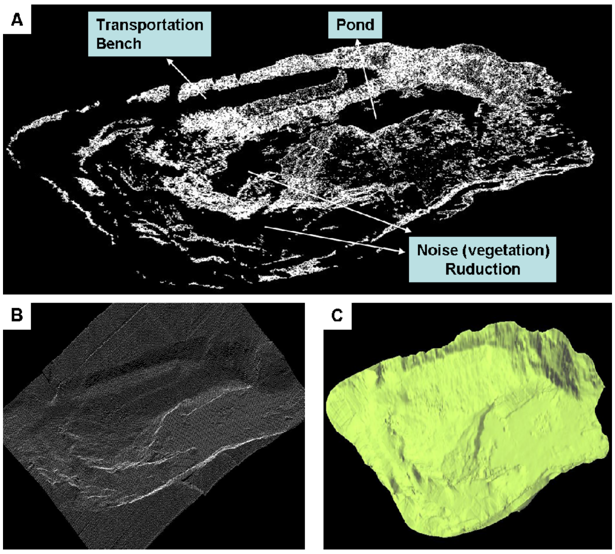

Figure 3. Visualizations after Kriging (B) and DSI (C) interpolation.

III. Geological and Geotechnical Applications

A. *Volume Calculation*

Volume calculation involving two aspects, such as quarry backfilling and spoil heap, does not need high resolution. In terms of backfilling, the volumetric mass we are focusing on is below the base level. In contrast, regarding spoil heap with convex geometry, volumetric body is above the base level. Consequently, it's key to determine the base level (i.e. covering plane to concave model in this case) for volume calculation. Various techniques have been utilized for creating covering plane in the following case where the volume of backfilling is calculated.

Currently, we can semi-automatically create covering plane through diverse techniques in different programs. For instance, PolyWorks creates covering plane by picking 2 view axis i.e. the covering plane parallels to the sea level if *x*-*y* axes are picked, or picking 3 anchors which fit the real boundary of quarry. GOCAD offers a better approach for creating covering plane because in this manner the boundary of covering plane is constrained by a number of points which are selected along the real quarry boundary (control points) and many points within the quarry are interpolated in light of the design requirement for remediation.

Fig. 4 shows two common methods for creating plane in PolyWorks. The first approach of picking 2 axes and the second one of picking 3 anchors are respectively given in A and B. However, no remarkable different skill exists between these two methods, the respective precision and volume results are different. In both two methods the covering plane can be moved along the *z* axis to be away or close to the lower 3DSM. In order to precisely calculate the volume, it is essential to get the rational sealing of covering plane to 3DSM which can not be accomplished by using these two approaches. Consequently, considerable computational error of volume depending on the magnitude of height (the yellow line, Fig. 4) from covering plane to 3DSM inevitably occurs.

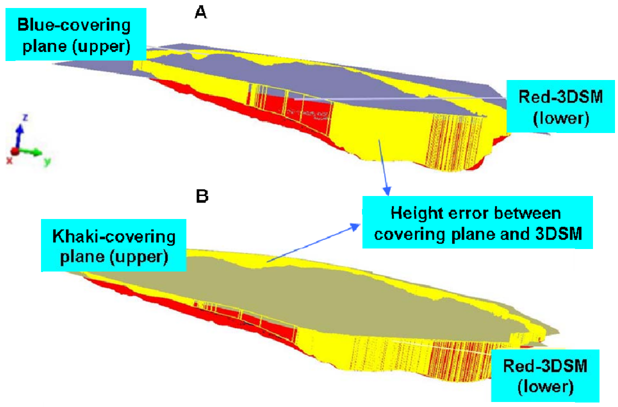

Figure 4. Two approaches for constructing covering plane in PolyWorks.

Contrarily, GOCAD can help users to deal with this problem and obtain a rational volume result which is useful for making decision of backfilling. Fig. 5 demonstrates that GOCAD offers the user with more advanced technique to calculate the volume due to the better sealing than other techniques. The amount of control points along the boundary depends on the required precision. The spatial position of control point coincides either with the quarry boundary or with harmonious difference for achieving the backfilled geomorphology. This technique is like creating a relief surface only based on control points in GOCAD. The *z* values of inner control points are synchronously set up in compliance with the designed relief. Comparing these techniques demonstrates that GOCAD not only creates the more rational covering plane but also computes more precise and practicable volume result.

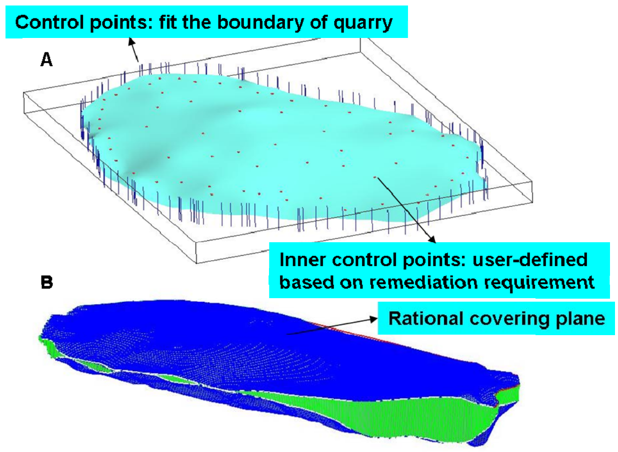

Figure 5. Better sealing technique for volume calculation in GOCAD.

B. *Slope Stability Analysis*

Slope stability analysis needs the medium resolution to create the 2D slope profile extracted from 3DSM which obviously plays an important role in geotechnical and geological applications. Finite element method (FEM) and limit equilibrium method (LEM) have been applied to assess the slope instability in this paper. The research site is the same as the case of volume calculation mentioned above. The transportation bench (width of circa 18m) located on the north side of the quarry area is heaped with soil of known physical-mechanical parameters shown in Tab. 2.

First and foremost, cross section should be manually set up on the 3DSM. In order to obtain more precise factor of safety, setting up more cross section along the whole bench for comparison is important. In this paper, two typical cross sections are selected for comparing the differences of results computed by both LEM and FEM.

GGU-stability (http://www.ggu-software.com/software/-geotechnical_software.html) (LEM platform) and ABAQUS 6.8 (http://www.simulia.com) (FEM simulation platform) are respectively applied into stability analysis with Janbu method and Mohr-Coulomb constitutive theory. Before evaluating slope stability, data transferring from 3DSM to the LEM and FEM software should be firstly achieved.

1) LEM and FEM slope stability analysis

Data transferring is much easier in LEM assessment than FEM due to that GGU can accept the CAD data file, such as DXF file format. Therefore, the bridge for connecting 3DSM and GGU is AutoCAD. In addition, GGU can search the slip surface automatically in short time. Factor of safety (FoS) calculation which is totally automated after model transfer to GGU is shown in Fig. 6 and the results are listed in Tab. 3.

Two main approaches of data transferring to ABAQUS have been proposed [13]. The first approach is making use of the third party software such as AutoCAD, the same as the method we use to transfer the model for LEM analysis. However this manner is easy to understand and manipulate, we will met some problems like model disorder and information lost especially for 3D model transferring. The second one is user's own interface programming which can transfer the 3DSM directly into ABAQUS without problems mentioned before. This method requires sufficient knowledge about INP file imported into ABAQUS and proficient capability of programming of researchers. FEM simulation and analysis which considers the relationship of strain and stress is more comprehensive and reasonable than LEM. Nevertheless, LEM is still one of the most popular and important means for slope stability analysis due to its ease to use and sufficient precision for engineering field. The FEM simulation model and the zone of equivalent plastic strain are shown in Fig. 7.

2) Results

Tab. 3 shows the results of safety factor based on LEM and FEM. The results computed by both FEM and LEM are close to each other with the acceptable differences. The homogeneity of material of heaped bench is thereupon proved. Moreover, the slip surface GGU (LEM) searches coincides with the zone of equivalent plastic strain visualized in Fig. 7 (FEM). It demonstrates that the results are useful for making decision and the proposed approaches for data transferring are effective and applicable.

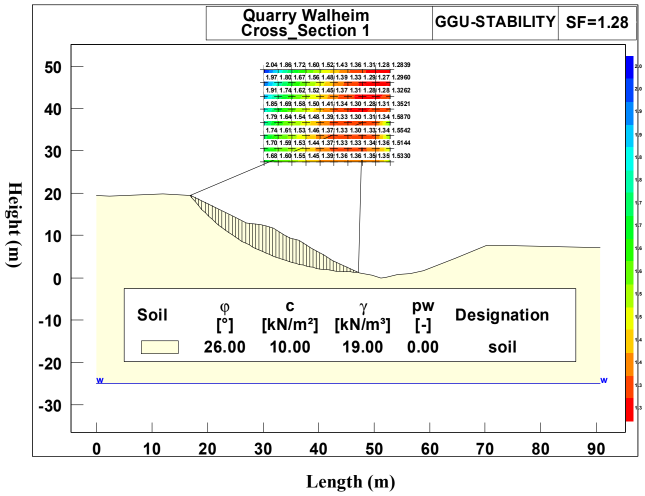

Figure 6. LEM stability computation in GGU.

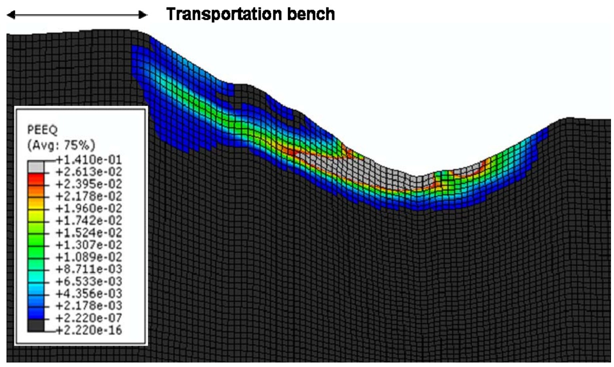

Figure 7. FEM stability simulation and computation in ABAQUS.

TABLE II. GEOTECHNICAL PARAMETERS OF BENCH MATERIAL

Mass Density (Kg/m^3)	**E** (Pa)	ν	**C** (Pa)	φ (°)
1900	$8*10^6$	0.45	10000	26

TABLE III. FACTORS OF SAFETY BY USING FEM AND LEM

Cross-Section		**1**	**2**
Factor of Safety	**FEM**	1.31	1.27
	LEM	1.28	1.29

C. Joint Analysis

In joint analysis case study, high resolution and quality of data set is needed. For the reason that large amount of data are sophisticatedly processed not as same as two previous cases, moreover the research area of this case is in Madeira different from Quarry Walheim, it is necessary to enunciate the whole processing for joint analysis as follows.

1) Discontinuity characterization on research site

As part of a rockfall hazard assessment investigation, automatic discontinuity characterizations of volcanic rock slopes have been done on the island of Madeira (Portugal). Owing to the entire island characterized by high mountain ridges and steep deep valleys in lavaflows and tuff layers, the occurrence of rockfall is a frequent and a serious problem. The analyzed slope is 60 m high and the length of 500 m (Fig. 8). It is built up of lava flows with column structures, intercalated breccias, and tuff layers. Many of the columns already lack basal support and show a wide joint spacing, threatening houses and streets in the city. Difficulties occur by limited accessibility to the exposed rock faces and a non persistence of the discontinuities due to the volcanic origin. It is obvious that taking advantages of TLS for acquiring data of this area is safe and effective.

Out of the analyzed slope only points of interest have been treated and analyzed separately. Points of interest are uncovered massive lavaflows with detectable discontinuities which have been scanned in high-resolution (Fig. 9). Separate treatment is necessary due to the enormous size of high-resolution scans. By automated discontinuity analysis for rock slopes (using Split-FX, Split-Engineering, 2008), present discontinuity systems can be quantified

2) Data analysis

Discontinuity characterization can be achieved by manually fitting planes on individual recognizable surface or traces in 3D models. The typical workflow for discontinuity characterization is presented in Fig. 10 (summarized from Slob et al. 2005).

Data acquisition in May 2008 provides detailed LiDAR data of the massive lavaflows. Data process is almost the same as mentioned in case 1 and 2. Eliminating gross error and reducing redundant data are generally done before registering all scans due to the mass data. Afterwards by using 3D Delaunay Triangulation to mesh the entire point clouds, strike and dip of each triangle can be measured. Grouping neighboring triangles with similar orientations results in joint faces of any size. By limiting the minimum number of equal neighboring triangles to measure and plotting their orientation in a polar plot, a series of clusters of joint face which represent different rock mass discontinuities appear. Using software to measure and plot automatically provides a human unbiased, rapid and accurate discontinuity analysis. With fuzzy k-means clustering algorithms and additional visual checked of dyed cluster sets on the 3D model, individual discontinuity sets can be identified. By removal of outliners through Fisher distribution, mean orientations of identified sets can be computed.

3) Results

Iterations of the workflow on volcanic rock faces result in the identification of five distinguishable column-bounding fractures and two column-normal fractures. While in single area of interest only parts of the overall joint faces are present, summarizing every mean discontinuity sets into a single stereo net shows their similarity and the overall present discontinuity system in the slope (Fig. 8 and 9). In addition, local and global characterizations show a general tendency to build up primary primitive columns with a horizontal spatial distribution between 0.5 m and 2 m based on photographical analysis and following spatial distribution. It is effective and efficient to use TLS and automated software for characterization of massive volcanic lavaflows along large slopes.

IV. CONCLUSIONS

Discussions from deployment of TLS in field scanning to procedures of 3DSM and then to a series of geological and geotechnical engineering applications, have demonstrated the following conclusions:

1. TLS is a dominant technology for surveying due to its inherent advantages, especially high resolution, efficiency and without facing the dangerous and busy site. Therefore it can be more widely used for geological and geotechnical engineering applications.

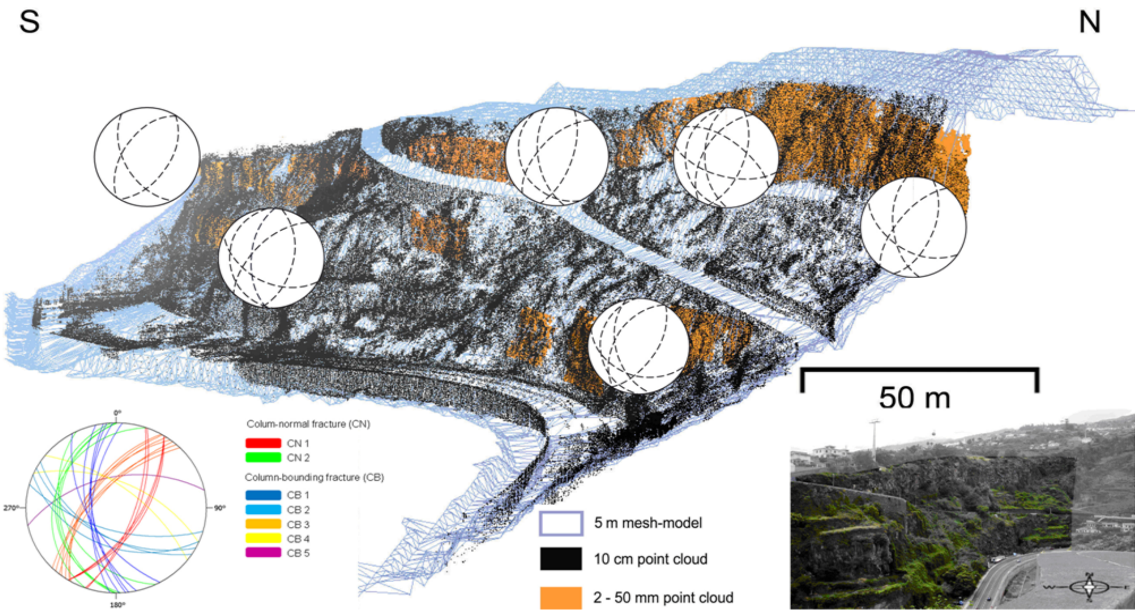

Figure 8. Slope discontinuities analysis in Funchal city, Madeira, Portugal.

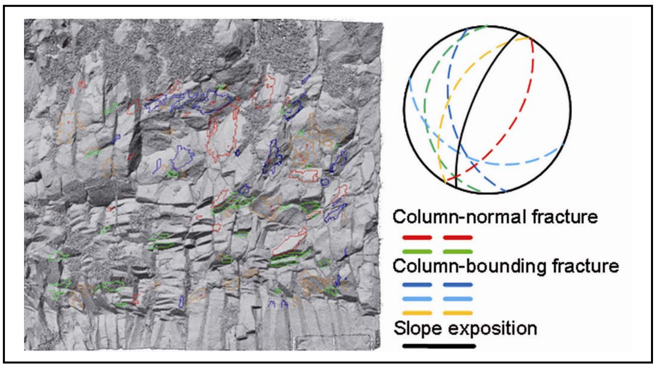

Figure 9. High resolution of discontinuity characterization on 3D model.

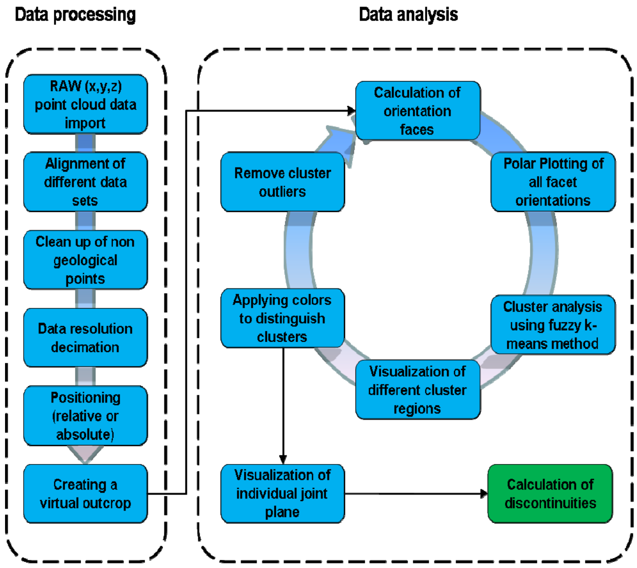

Figure 10. Workflow of discontinuity analysis based on LiDAR data.

2. 3DSM creation with different resolution plays an important role in the further applications. 3DSM can not only offer users with geometrical characteristics which are involving the volume calculation and slope stability analysis in this paper, but also more information (such as strike and dip information) which is useful and related to the joint analysis application.

3. GOCAD provides a better solution for creating covering plane which fits seamlessly with the boundary of research area. Therefore the corresponding volume calculation is more precise.

4. Using the third party CAD software to export specific file format like DXF can efficiently solve the problem of data transferring between 3DSM and LEM or FEM platforms; on the other hand, our own programming facilitates 3D data transferring from 3DSM to the platform of user's final aim.

5. Combining TLS with automated software is effective and efficient approach for characterizing and quantifying of massive discontinuities.

ACKNOWLEDGMENT

Many thanks to EUROVIA Industrie GmbH for field support.

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