Accurate rock mass structural characterization based on 3D point cloud model from remote sensing techniques

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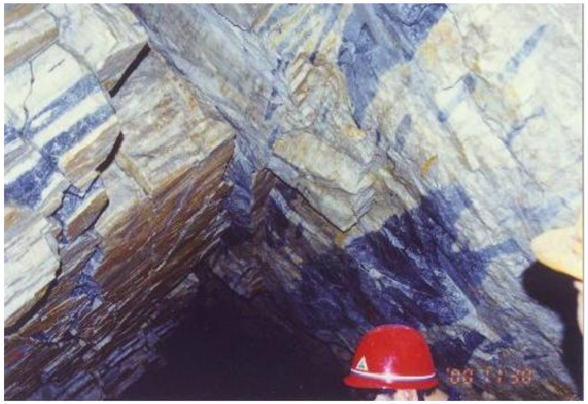
Research Background

Structural and mechanical analyses of rock mass are key components for rock deformation, hydraulics and stability assessment.

Accurate quantification of discontinuity characteristics have been always required.

A massive granite slope



A thick layered marble tunnel

An unstable rockfall

Research Background

The traditional manual survey (Contact measurement) by compass and tape measures just in accessible area can sometimes be a biased, time consuming and limited in its coverage method.

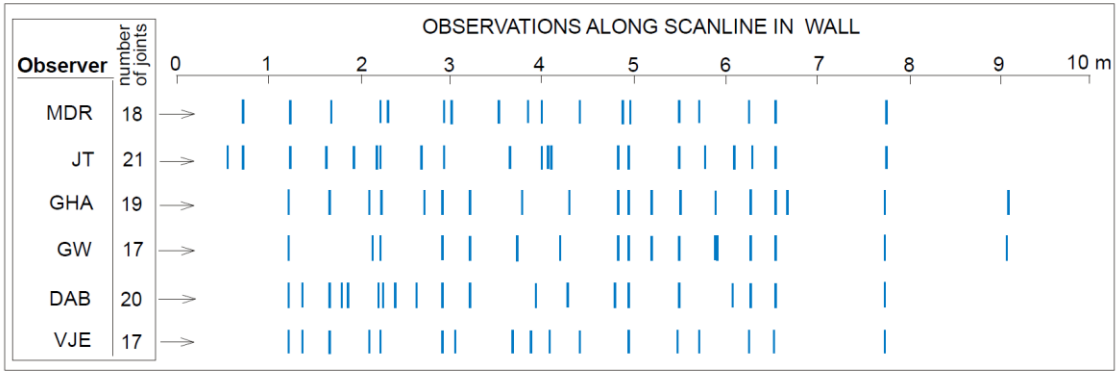


After Wenchuan Earthquake, in Sichuan, China, 2011

Scanline survey (M.Noroozi, 2015)

- Time-consuming, laborious and possibly dangerous.
- Direct access to rock faces is sometimes hard if not impossible,
- The measuring range is often limited at the toe of slopes.

Research Background



(Ewan et al. 1983)

Ewan et al. (1983) report from an interesting investigation to see the reproducibility of joint parameters measurements.

They found that the number of joints recorded could vary by up to a factor of four for different observers measuring the same scanline.

Clearly it is necessary to reduce the subjective element of joint measurement by measuring all fractures that cross the scanline.

The subjectivity cannot therefore be eliminated, only minimized.

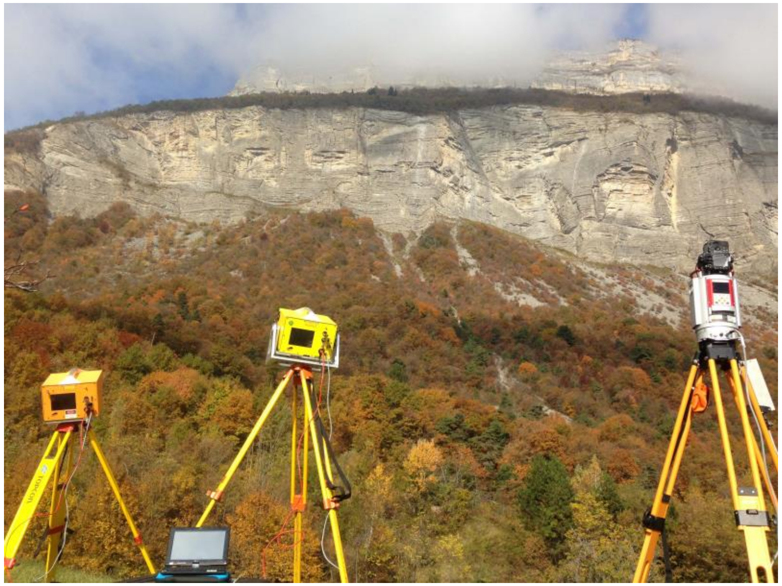
- Human errors are inevitable and the reliability and accuracy of data rely heavily on the geological experience of the surveyors.

Research Background

Alternatively, remote-sensing techniques such as digital photogrammetry, Light Detection and Ranging (LiDAR) technique and Unmanned Aerial Vehicle (UAV) technique

Obtain high accuracy and spatial resolution of 3D information

3D Model 3D point clouds



Optech MR, Optech LR, and RIEGL VZ-2000

DJI UAV survey, 2018

Research Background

A new method for Automatic identification and extraction of rock mass discontinuities from 3D point clouds:

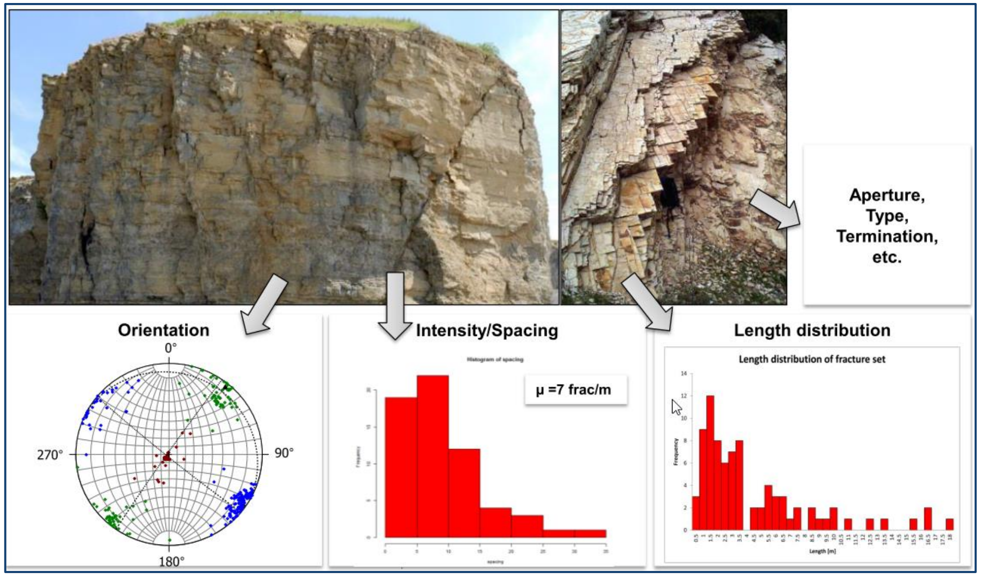


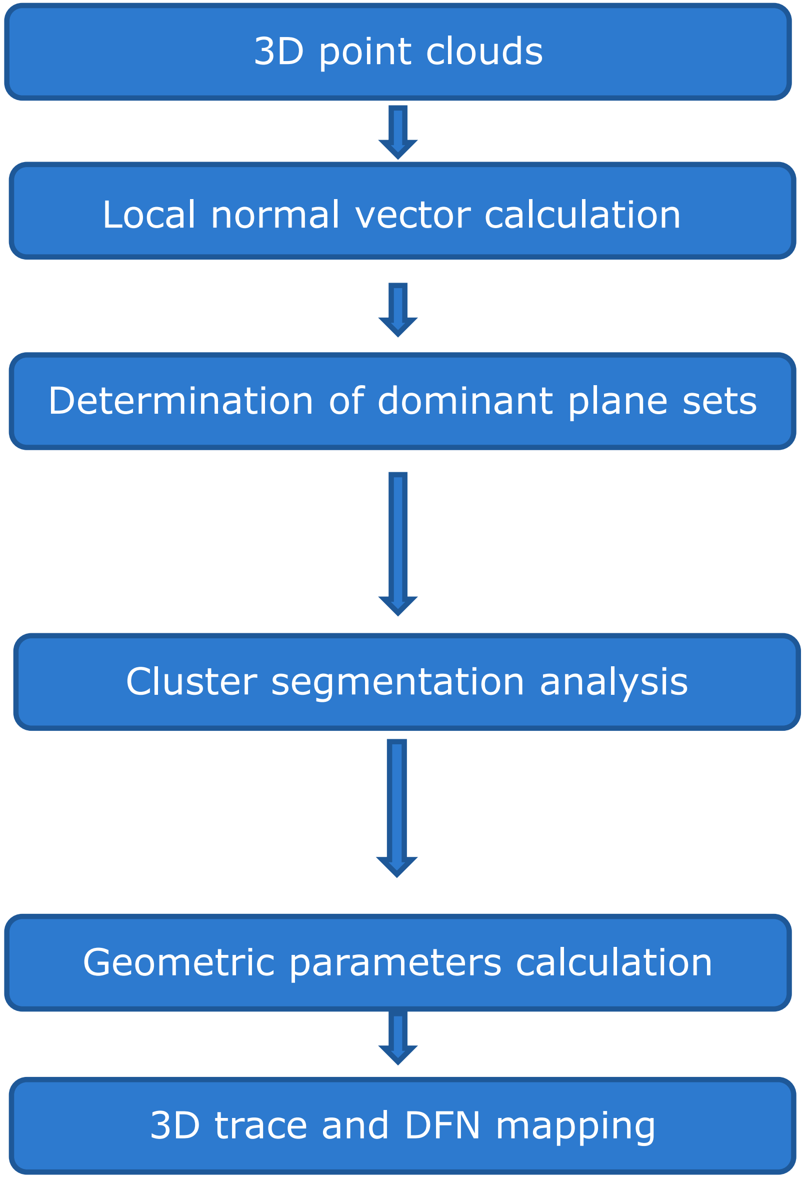
Figure from Dennis Laux & Andreas Henk, 2014

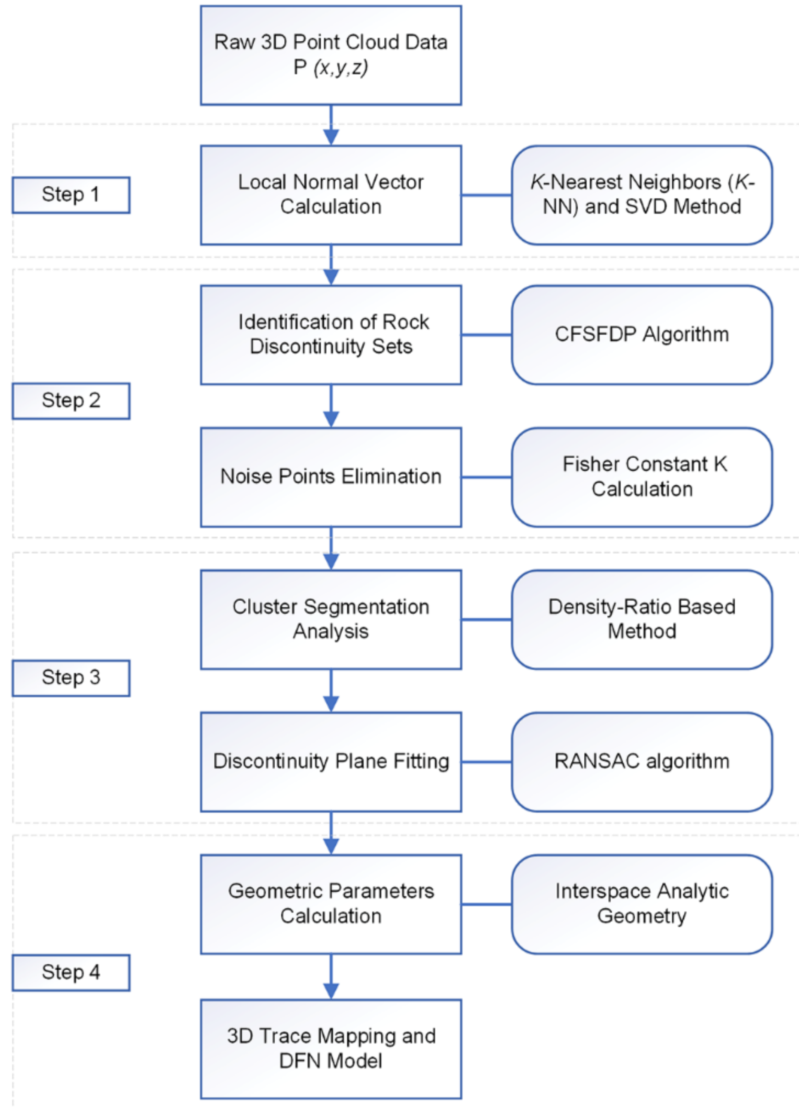
ISRM (1978) proposed a suggested method for the description of geometrical, mechanical and hydraulic features of discontinuities, consisting of the following ten parameters: orientation, spacing, persistence (or trace length), roughness, aperture, wall strength, filling, seepage, number of fracture sets and block size.

Nine parameters

Discontinuity sets
Orientation
Persistence (Trace Length)
Set Spacing (density)
Linear frequency P_{10}
Areal frequency P_{20}
Areal intensity P_{21}
Aperture of open joint (from high-resolution images)
In-situ block size

Methodology





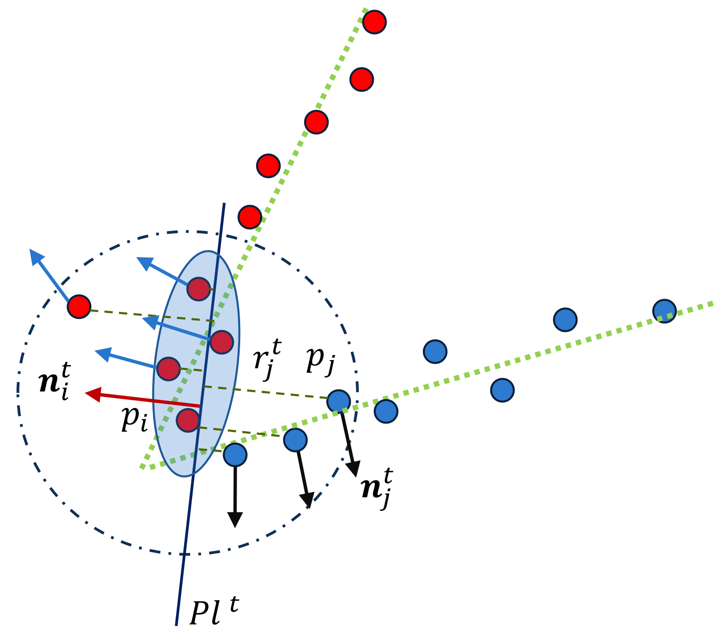
Methodology

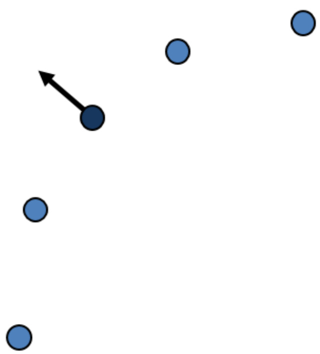
Local normal vector calculation

$$Pl(d^t, \mathrm{n}^t) = \mathrm{argmin}\sum_{j=1}^{k} r_j^t w_d(p_j) w_r(r^t{}_j^{-1}) w_n(\boldsymbol{n}^t{}_j^{-1}) \qquad \|\boldsymbol{n}^t\| = 1$$

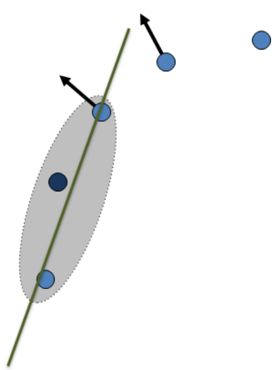
An adaptive normal estimation method related with distance, fitted residual, and normal difference weights is developed.

The developed method has been demonstrated to be robust towards noise and outliers in the scanned point cloud and capable of dealing with sparse point clouds.

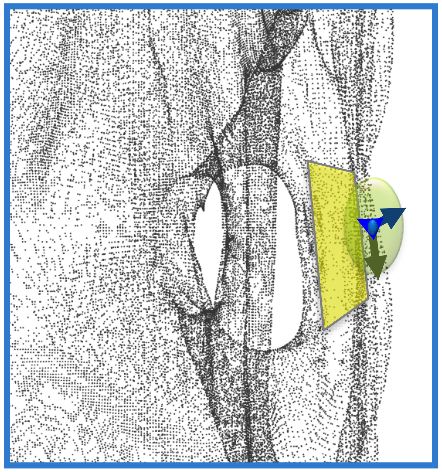




a set of 3D points
$P = \{p_1, p_2, \dots, p_i, \dots, p_N,\}$



$N_k(p_i)$, *k nearest neighbors*

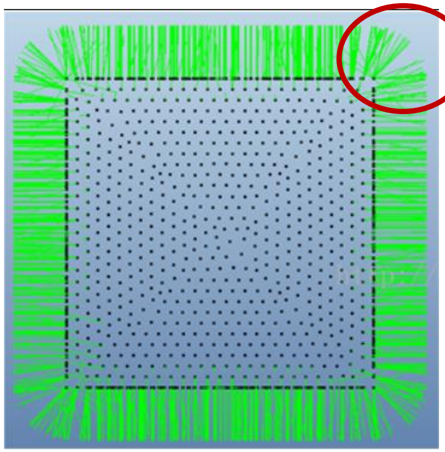


the normal vector $n_i(l, m, n)$ *of* $N_k(p_i)$

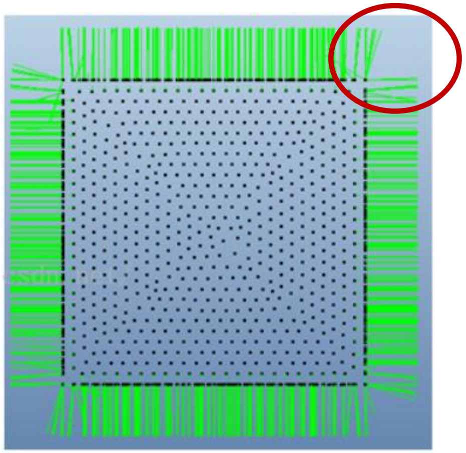
Methodology

Bilateral normal smoothing method is utilized to effectively correct noise, provide reliable normals.

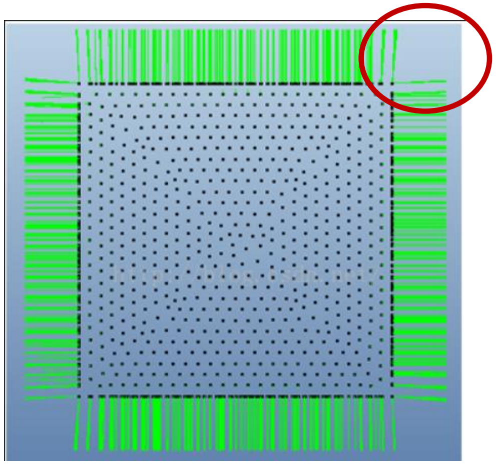
$$\mathbf{n}_i \leftarrow \frac{\sum_{s_{i'} \in \mathcal{N}_{s_i}} \theta(\|p_i - p_{i'}\|)\psi(\mathbf{n}_i, \mathbf{n}_{i'})\mathbf{n}_{i'}}{\sum_{s_{i'} \in \mathcal{N}_{s_i}} \theta(\|p_i - p_{i'}\|)\psi(\mathbf{n}_i, \mathbf{n}_{i'})}$$



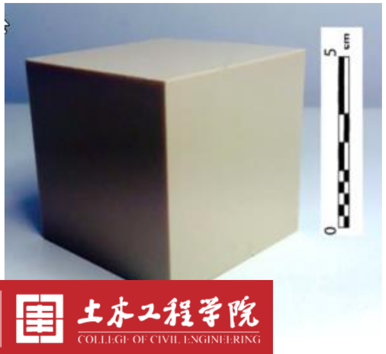
(a) Regular PCA normals

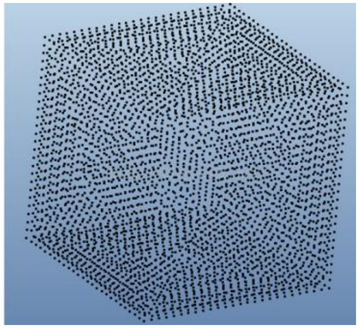


(b) Gaussian weights based normals



(c) Bilateral normal smoothing normals



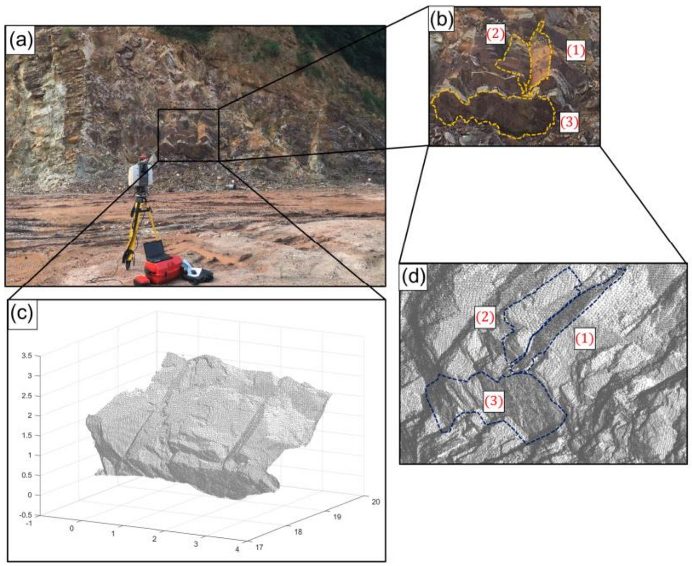


Data source files (XYZI) acquired by LiDAR.
From Riquelme, A. J. 2014

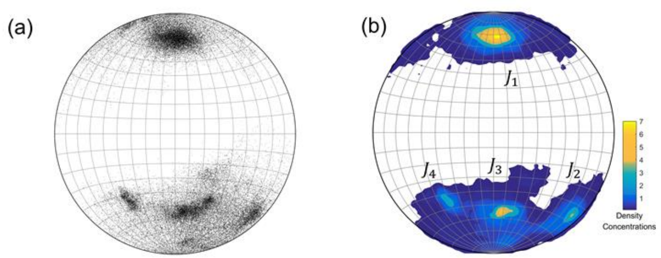
Methodology

Determination of dominant plane sets

Clustering by Fast Search and Find of Density Peaks algorithm (CFSFDP, Alex Rodriguez, 2014) is used for the identification of the main discontinuity sets.



A rock slope as well as its point cloud data obtained by terrestrial laser scanning are selected as experimental dataset for methodology explanation.

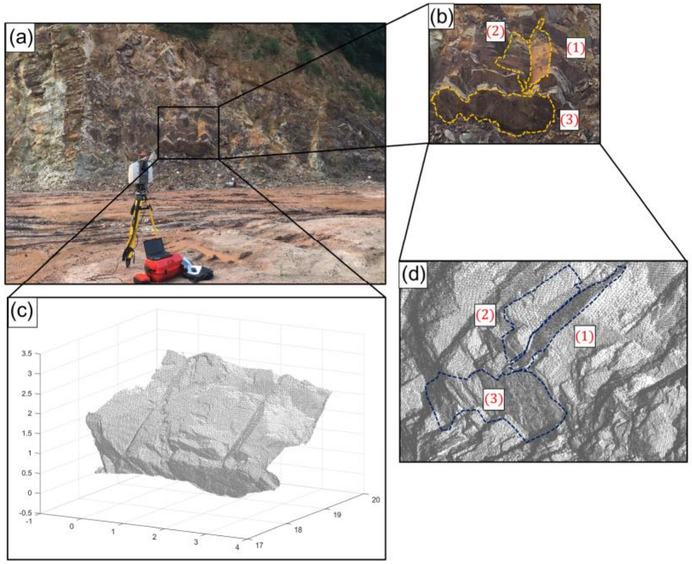


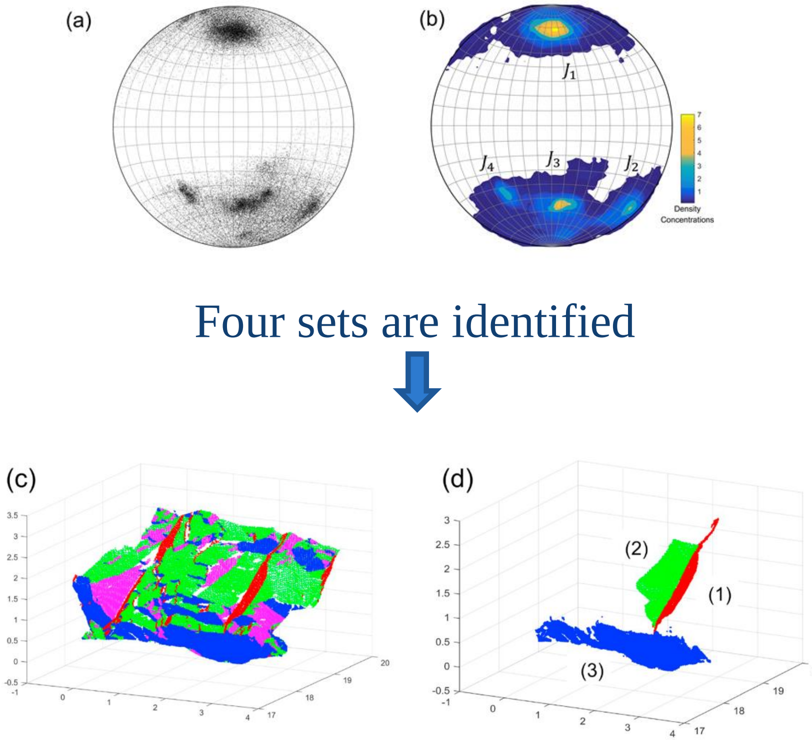
Four sets are identified

Methodology

Determination of dominant plane sets

A density-ratio based method which has the capacity to identify all the clusters from a point dataset of largely varying densities is applied .





Four sets are identified

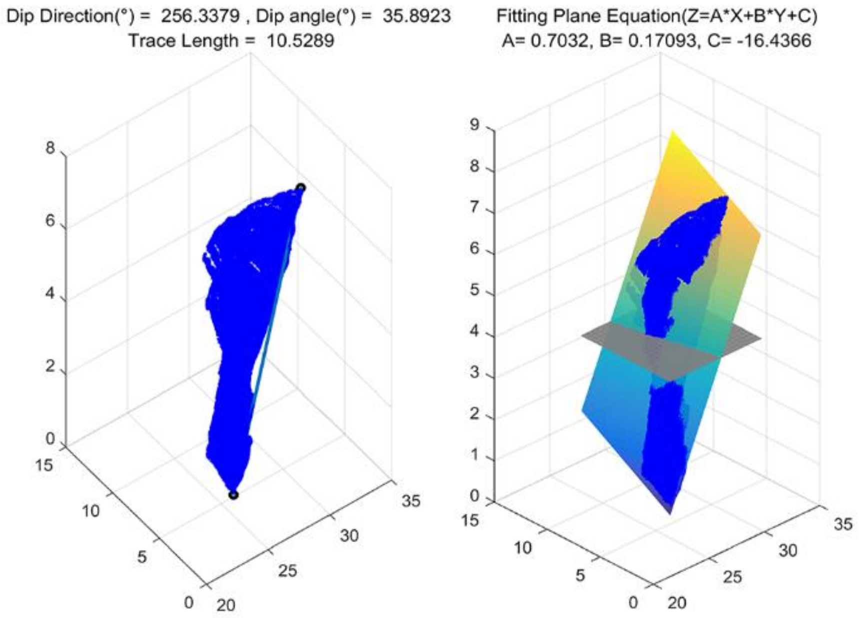
Automatic identification of three discontinuities

Methodology

Trace length and spacing calculation

Minimum sphere ball is used to calculate trace length. And the diameter of the ball is taken as the trace length.

$$TL = max\colon d(p_i, p_j) = ||p_i - p_j||_2 \ \forall\, i, j \in \{1, \ldots, t\} \qquad TL, d \in \mathbb{R},\ t \in N$$



one joint orientation and trace length calculation

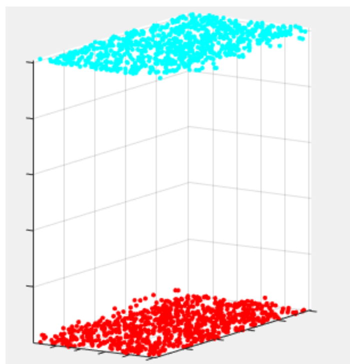
Minimum sphere ball of one joint

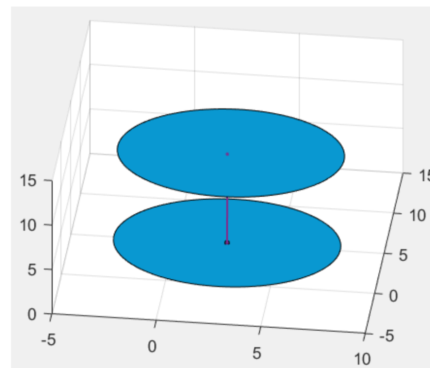
Methodology

Set spacing: distance between subsequent discontinuities or average spacing between discontinuities from the same set.

Random Sample Consensus (RANSAC) algorithm (Fischler and Bolles, 1981) for plane fitting takes the waviness and volatility of the points into consideration and provides a more realistic estimation.

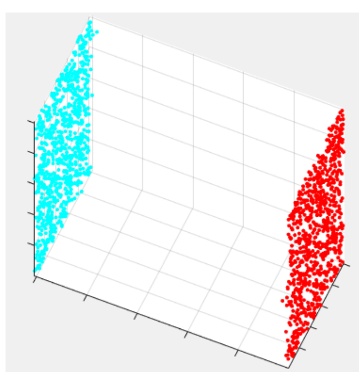
set 1

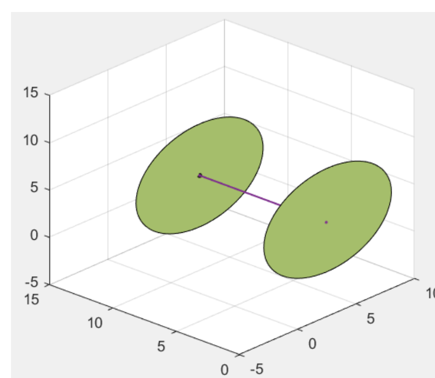




Spacing calculation

set 2





An example

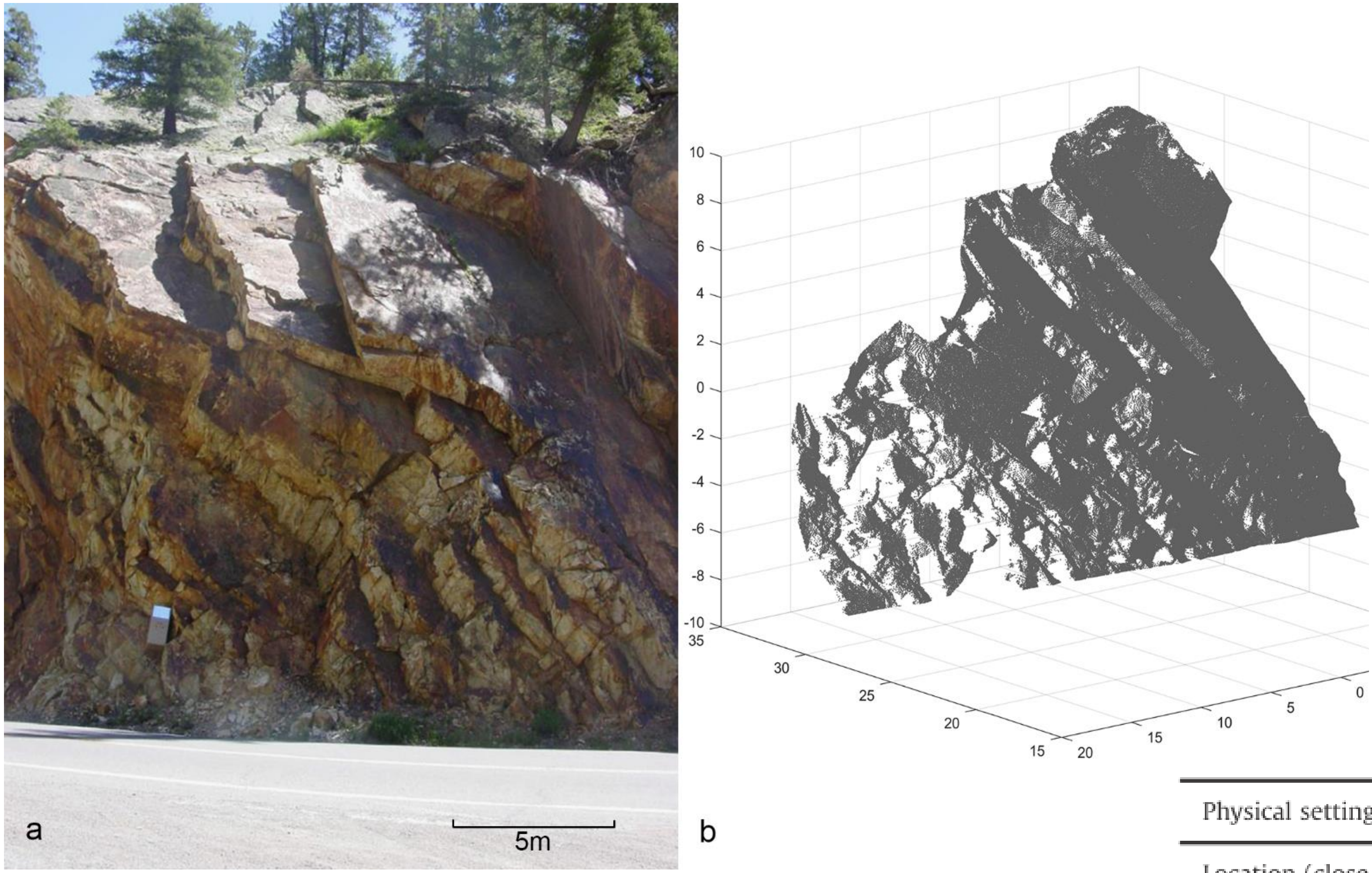
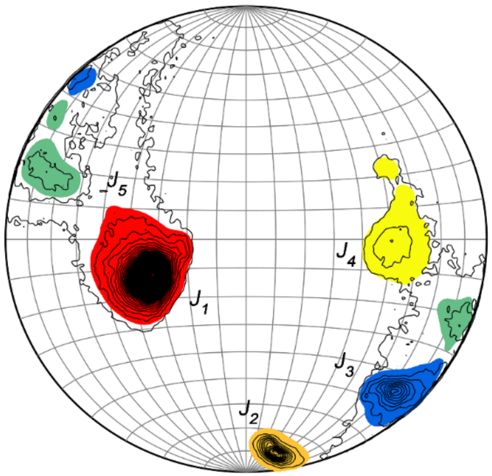


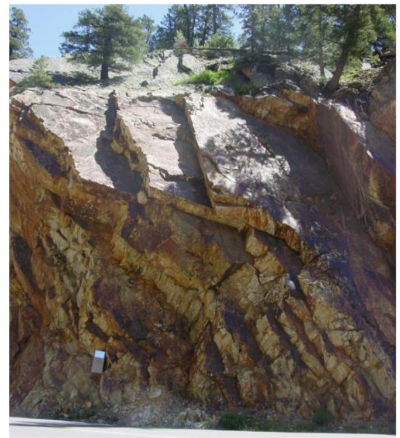
Photo and 3D point cloud of this slope. Data file from Rockbench Repository.

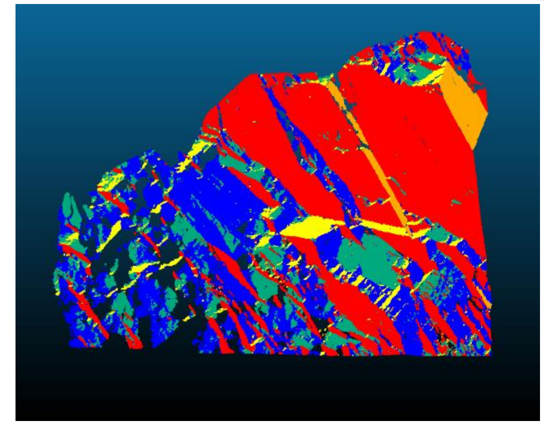
Physical setting	Roadcut
Location (close mjr. City)	Ouray, Colorado
Lithology	Quartzite
Scanner	Optech
Laser type	Time of flight
Year scanned	2004
# of scan locations	4
Point spacing	< 2 cm
Number of points	1,515,722
Collected by	John Kemeny
Dataset	10a

Another case study was carried out using LiDAR data at Rockbench Repository.
This case study consists in a real rock cut located in Ouray, Colorado, USA.

An example







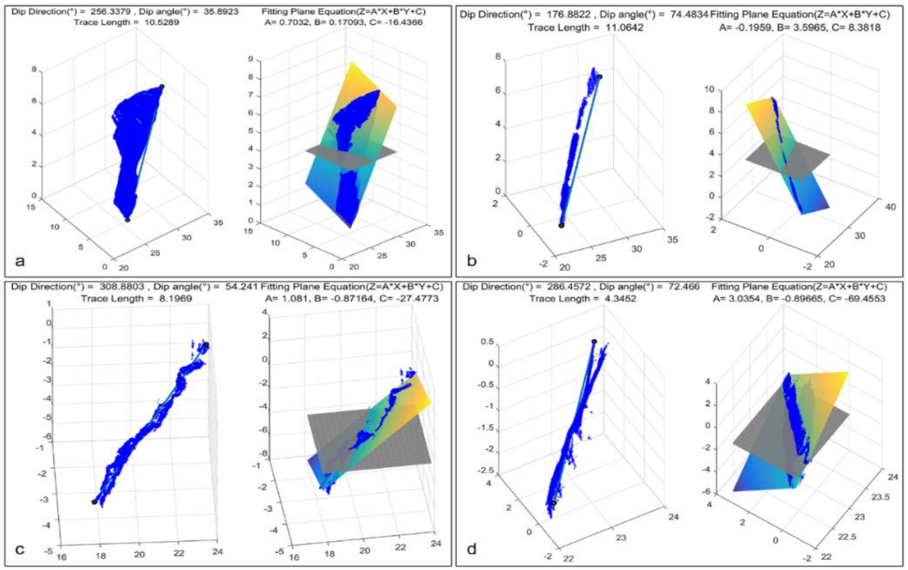
Five dominant discontinuity sets are identified

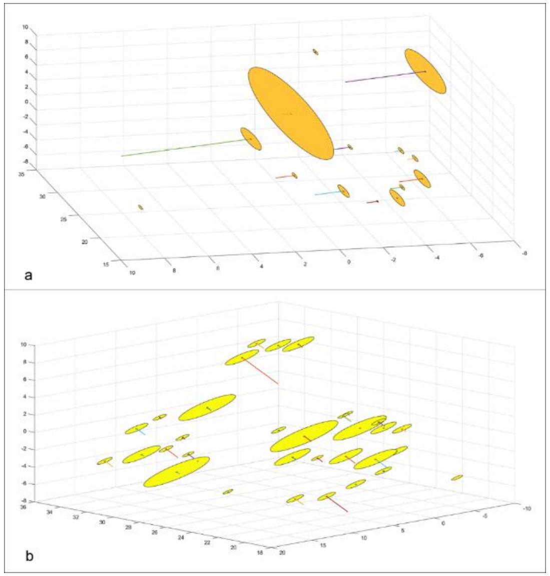
Sets	Results by Riquelme (2014)	The proposed method	Difference	
	Dip dir /Dip (°)	Dip dir /Dip (°)	Δ|DD|	Δ|DA|
J_1	249.04/36.66	248.44/34.71	0.6	1.95
J_2	172.29/83.16	172.51/81.34	0.22	1.82
J_3	137.33/77.87	135.45/82.90	1.88	5.03
J_4	92.96/48.74	90.82/51.06	2.14	2.32
J_5	288.45/68.22	288.23/72.74	0.22	4.52

The results are almost the same, and deviation value of dip direction is about 1° to 2°, and deviation value of dip angle is about 1° to 5°.

An example

Every single discontinuity orientation and trace length

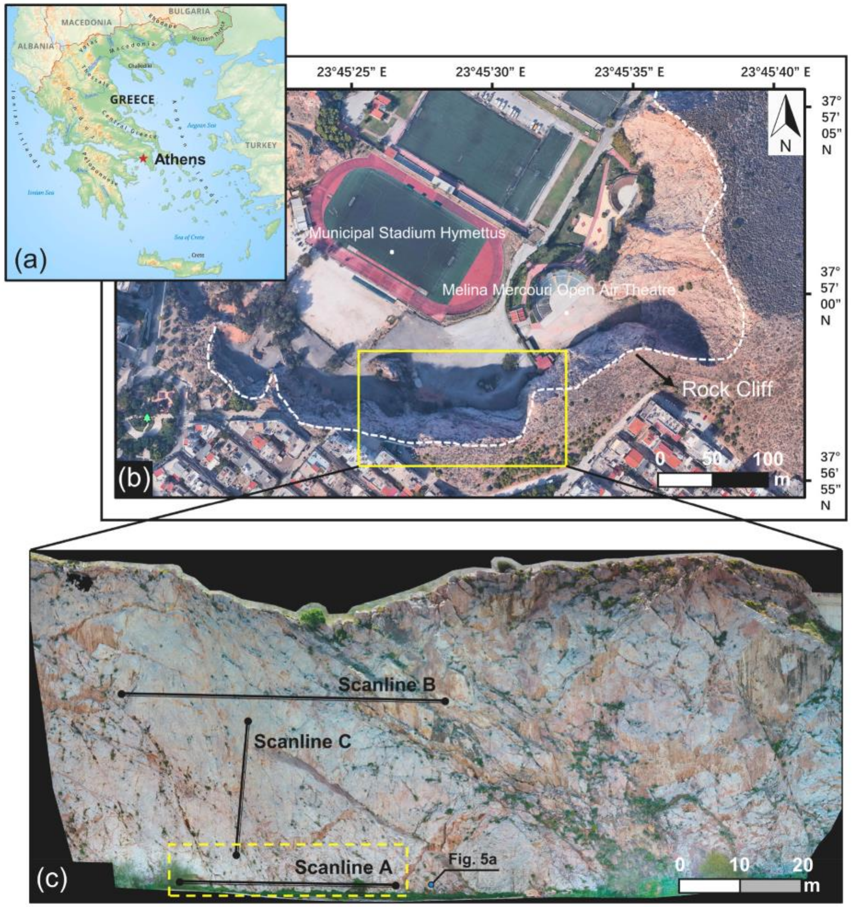


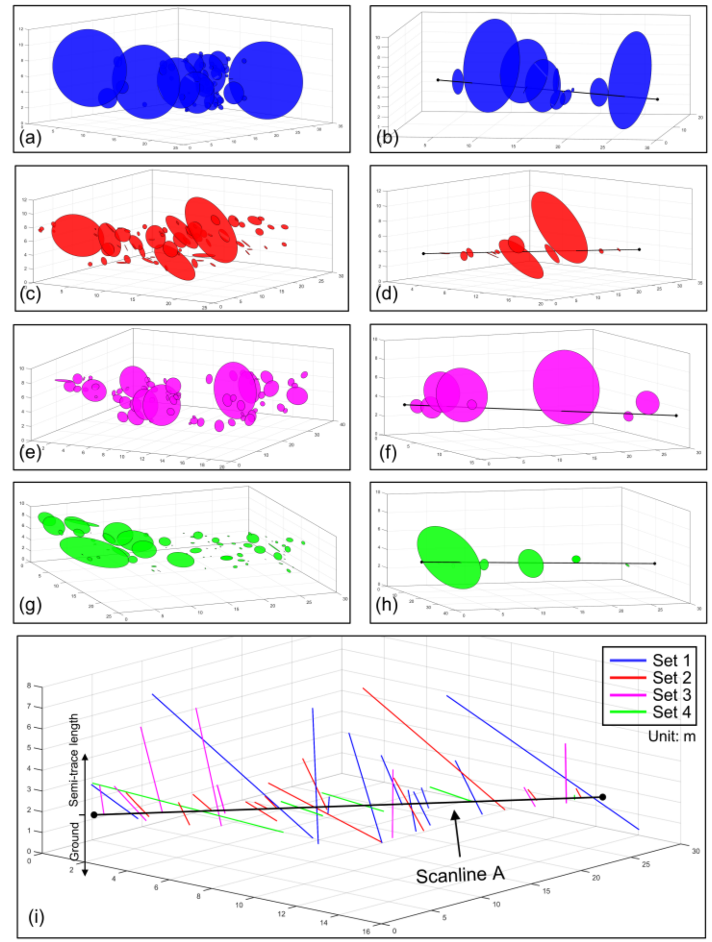


No.	Set	Location			Orientation	Trace length (m)
		x	y	z		
a	J_1	27.6720	6.2147	4.0846	256° /36°	10.53
b	J_2	26.0937	-6.7581	6.0475	177° /74°	11.06
c	J_3	27.0294	8.0901	-0.1330	309° /54°	8.20
d	J_5	22.6070	1.3540	-2.3046	286° /72°	4.35

Digital sampling from 3D point cloud

Scanline sampling

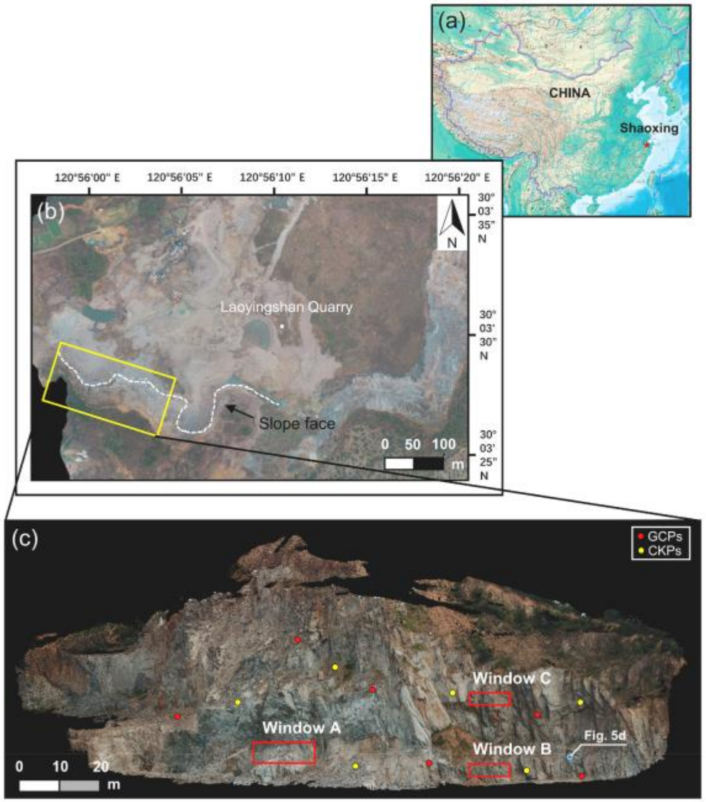


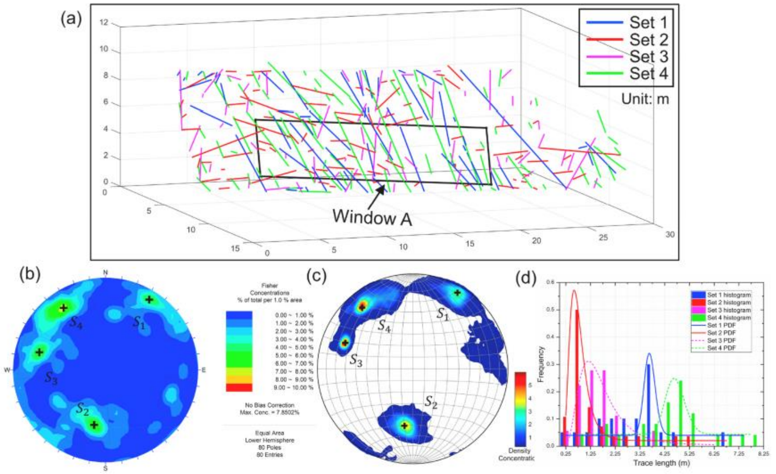


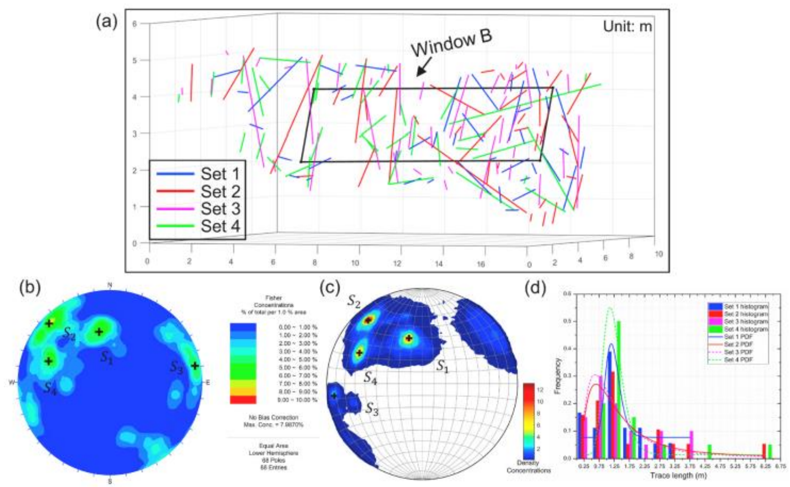
Each discontinuity is fitted to disc using the exposed discontinuity length as the diameter, and the orientation as disc plane attitude. The 2D digital traces are formed by intersections between the discontinuity discs and the fitting plane of the slope face. Subsequently, the digital trace mapping can be established. A virtual scanline with a fixed length was placed on the slope face plane, and the locations of two endpoints stay consistent with the actual scanline in the field survey. The discontinuities that intersect with the scanline were filtered from digital trace mapping, and the number, orientation, and trace length values were acquired.

Digital sampling from 3D point cloud

Window sampling





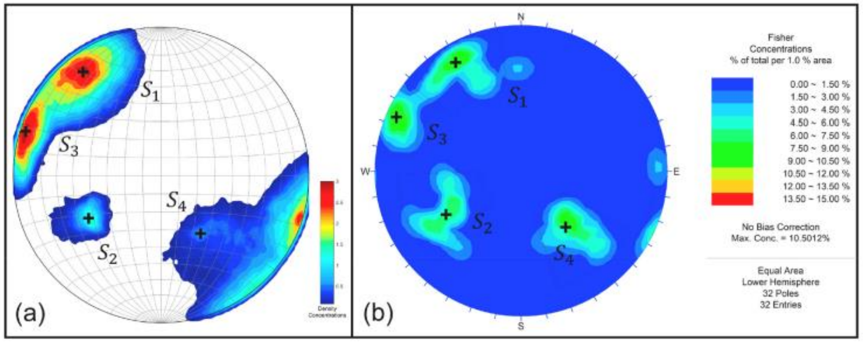


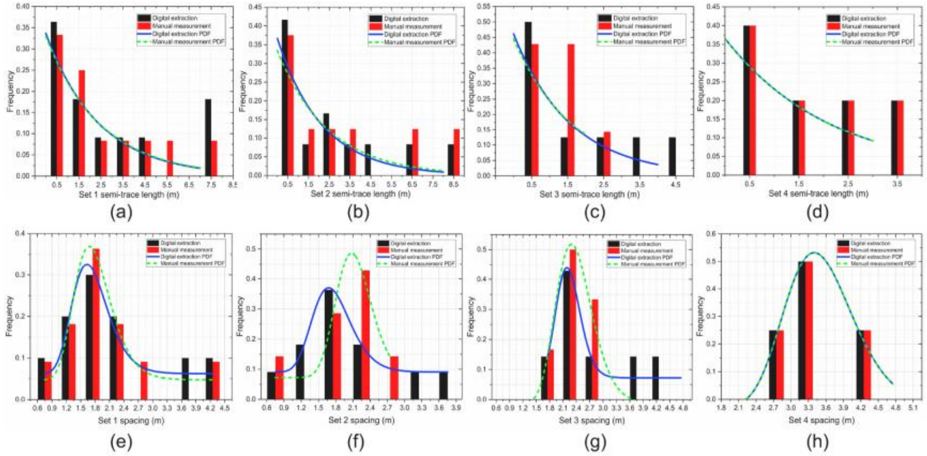
To achieve the window sampling from digital trace mapping, a rectangle window was placed on the slope face plane. The locations of four vertices stay consistent with the actual window in the field survey.

The location, midpoint, trace length and orientation of each discontinuity trace were acquired.

The values of P20 and P21 can be simply calculated from digital sampling map.

Extensive comparisons





The comparative results between field and digital measurements indicate that

- The average deviations are < 5 ◦ for dip direction and dip angle,
- The most deviation trace length value is less 0.10 m.
- The deviations for set spacing and P10 are < 0.40 m and < 0.10 m-1, respectively.
- Most deviations for P20 and P21 are < 0.06 m-2 and < 0.15 m-1, respectively.

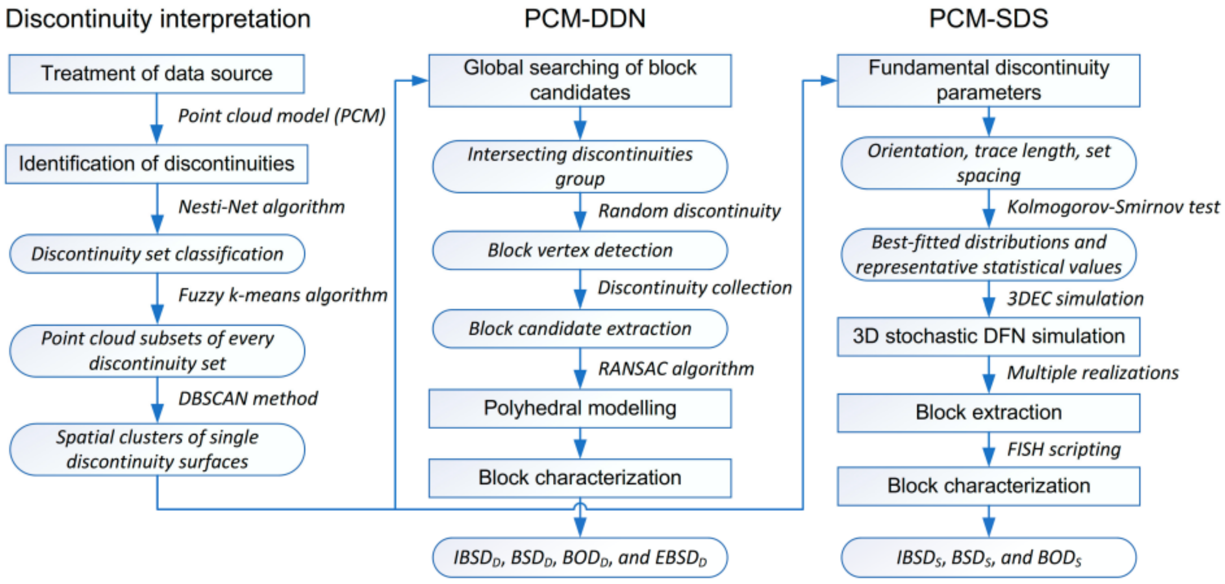
These well-matched results indicate that the digital analysis of our method can effectively identify and characterize the rock mass discontinuities.

In-Situ Block Characterization

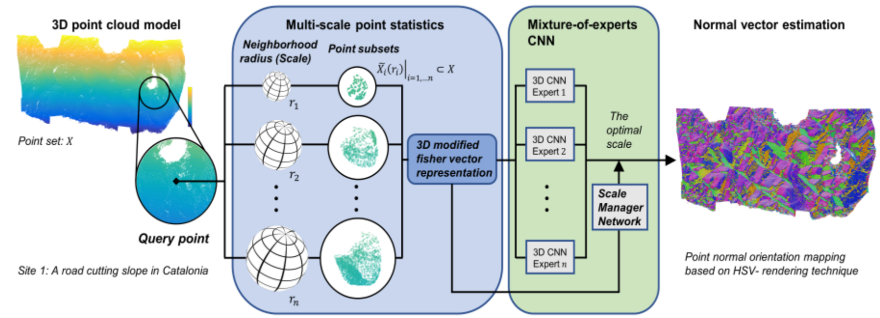
We developed a consistent and comprehensive method for rock block characterization that is composed of two different procedures and a block indicator system.

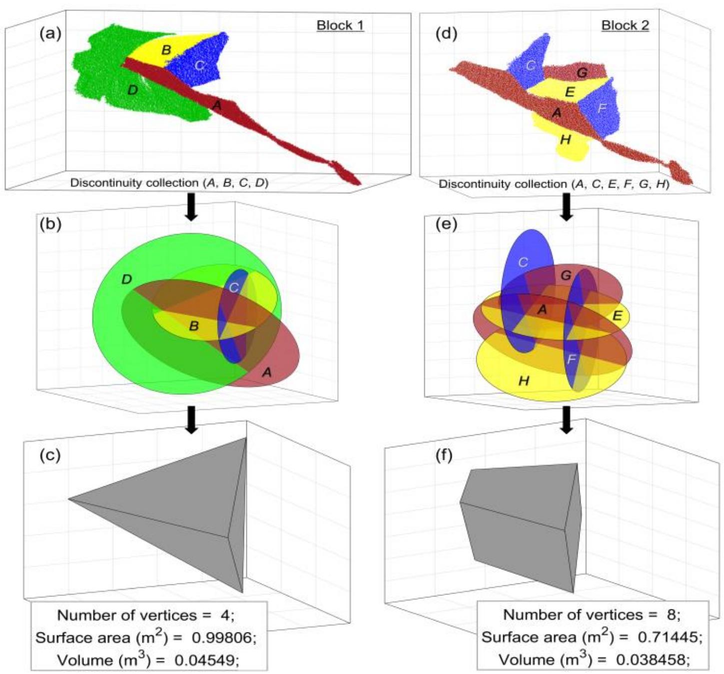
A semi-automatic procedure towards the robust extraction of in-situ rock blocks created by the deterministic discontinuity network on rock exposures (PCM-DDN) was developed.

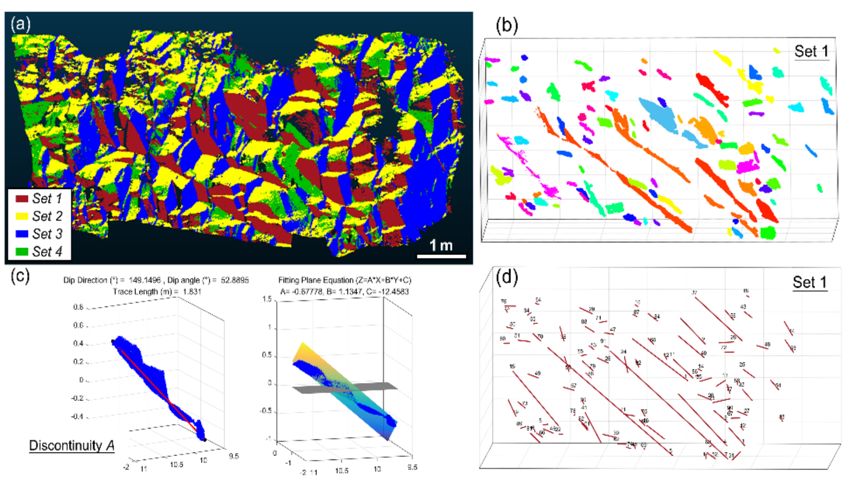
A 3D stochastic discrete fracture network (DFN) simulation (PCM-SDS) procedure was built based on the statistically valid representation of the discontinuity network geometry.



PCM-DDN method



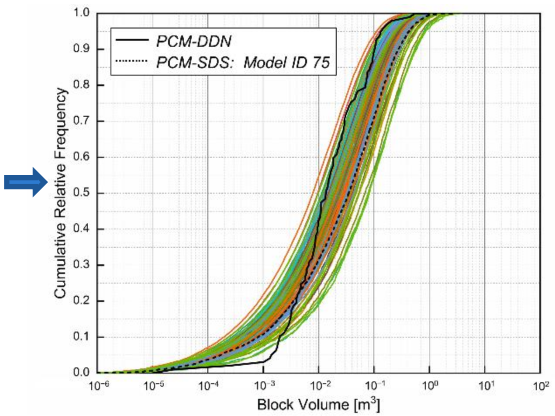




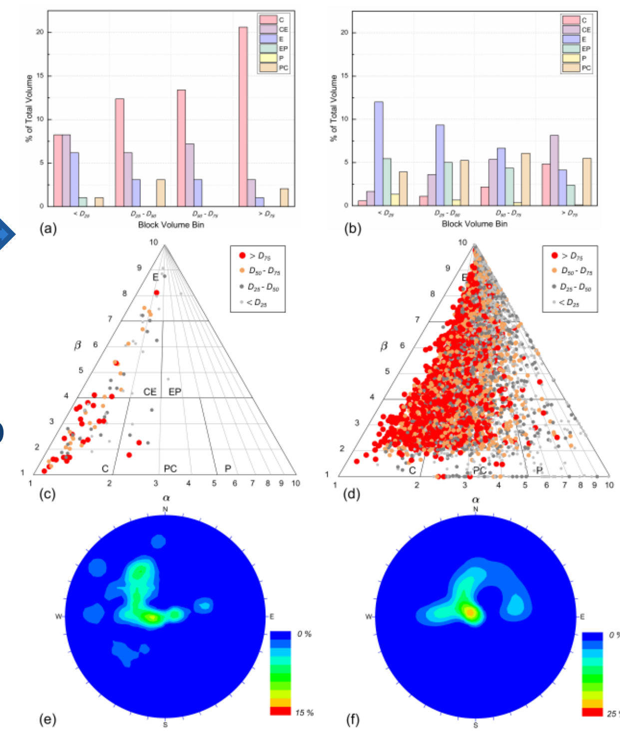
PCM-DDN method that presents the existing rock block reconstruction of full-scale rock exposure, in accordance with the mutual intersection relationship of discontinuities. This procedure describes the initial state of rock blocks in detail and reveals the structural complexity of the entire rock surface.

Block indicator system

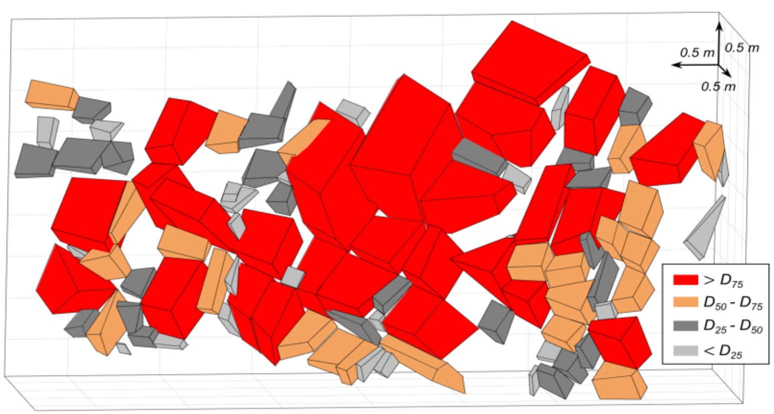
A multi-dimensional block indicator system for comprehensive block characterization, i.e., IBSD, block shape distribution (BSD), and block orientation distribution (BOD), is introduced, and the exposed block spatial distribution (EBSD) is mapped.



IBSD



BSD



EBSD

BOD

Conclusions

During this study,

1. A new approach for automatic identification and extraction of rock mass discontinuities, clustering of discontinuity sets and characterization of discontinuity orientation, persistence and spacing using 3D point cloud data is presented.
2. Each discontinuity parameters, such as location, orientation, trace length, spacing also can be input to create DFN model or conduct numerical simulation and stability assessment.
3. We also developed a multi-dimensional block indicator system for systematic and objective block characterization. These block indicators are simple and dependable, facilitating easy automation. These indicators demonstrated their potential for related research, such as rock mass quality classification, stability analysis, or blasting design in quarrying and excavation.
4. This study attempts to introduce the light-weight remote sensing technique into the rock mass characterization, the development of which in the future may become an important part in the next-generation field survey methods.

Thank you very much for attention!

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