Block in Point Cloud Data (BLOCKinPCD): A digital characterization system for rock outcrops

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ABSTRACT: The extraction of 3D block structure from a point cloud is a nontrivial but important task in rock engineering. Block in Point Cloud (BLOCKinPCD) is a novel processing system that converts the point cloud data of rock outcrops into 3D rock structure. The workflow and processing functions include: (1) spatially identifying and extracting the point clouds of each discontinuity set; (2) quantifying the geometric parameters of each set (orientation, spacing and persistence); (3) characterizing the in-situ block system by assembling the block-forming sets into discrete fracture network; (4) quantifying the volume distribution of the block system and (5) evaluating the stability of blocks intersecting the excavation surfaces. As shown herein, BLOCKinPCD has been successfully applied to outcrops exposed in rock slopes and tunnel excavations.

Keywords: Remote measurement, point cloud, rock structure, block system.

1 INTRODUCTION

One of the challenges in rock engineering relates to the spatial variation of rock structure, which cannot always be characterized in the investigation and design stages. Often, as in the case of tunnel excavation, rock structure details are only revealed during construction. Once the rock is exposed by tunneling, joint traces can be mapped, as a basis for quantifying the near-surface 3D block structure. In addition, the behavior of the in-situ block system after the excavation is the basis for judging whether to update the construction and support plan.

Traditional scanline surveys provide information pertaining to the frequency of discontinuities, normally over a range of tens of meters. The related processing methods introduced more than 40 years ago (Hudson & Priest 1983) provide estimates of the full range of discontinuity frequency variation, including the directional magnitudes of the maximum and minimum frequencies. The trace length estimation (Pahl 1981) based on window mapping provides a foundation for inferring the area size of discontinuities in 3D space. Fracture system modeling (Dershowitz & Einstein 1998) is a methodology developed to statistically combine geometric characteristics of shape, size, location and orientation of discontinuities as a computer model of the fracture network at a particular location.

The remote collection of rock structure data using geomatics techniques such as LiDAR and digital photogrammetry can capture outcrop details as point clouds with high resolution and accuracy. Compared with scanline and window surveys, the digital spatial data can achieve full coverage of large domains in a common coordinate system. As enumerated herein, an advantage of complete domain coverage relates to avoidance of errors arising from combining field measurements from individual outcrops. More importantly, the point cloud of the entire domain in a common coordinate system greatly facilitates the location-dependent extraction of the fracture network and computations of the in-situ block system.

2 EXTRACTING 3D BLOCKS FROM POINT CLOUD

For the processing of point cloud-based rock mass discontinuity patterns and subsequent reconstruction of the in-situ block system, a workflow referred to as Block in Point Cloud (BLOCKinPCD) has been developed (Fig. 1).

Step 1: calculate the normal orientation (dip direction / dip) of each point

Step 2: color each point in the HSV color space according to its normal orientation

Step 3: cluster the orientation sets and extract the set-based points

Step 4: process the set-based parameters including orientation, persistence ratio and spacing.

Step 5: identify how the discontinuities are spatially organized to cut the rock into blocks

Step 6: compute the mean block size and block size distribution, or accurately estimate block volume along with kinematic removability and stability.

Figure 1. Workflow of BLOCKinPCD.

The first step in modeling the rock structure directly from a point cloud is to estimate the direction of each point in space, which is the normal vector perpendicular to the surface on which the point is located. Points on the same discontinuity can then be filtered according to their direction similarities. To compute the normal of a point within the point cloud, it is necessary to consider neighboring points. The Hough transformation implemented in Boulch and Marlet's algorithm (Boulch & Marlet 2016) identifies planar surface regions and reconstructs intersection edges between the block-forming discontinuities (Dong et al. 2019).

The second step is to represent the 3D rock structure using the HSV-color wheel (Liu & Kaufmann 2015) shown in Fig.2. With the HSV color wheel, the hue (H) represents the dip direction of a point and the saturation (S) represents the dip magnitude. Point orientations are thus rendered by a unique color, and points defining a discontinuity set will have a similar color. The 3D rock structure is represented by the resulting overall color pattern.

In the third step, the 3D vector clustering method in statistical mathematics (Hornik et al. 2012) is applied to objectively identify the points belonging to the same set (which can be extracted from the point cloud). The relevant set-based geometric parameters include orientation, spacing and persistence ratio.

Step 4 involves calculation of the set-based orientations using automated R algorithms (R Core Team 2022). Measurements of spacing and persistence ratio are performed digitally on the computer screen. The persistence ratio represents the proportion of the area of the discontinuity plane or the length of discontinuity trace present, relative to a characteristic area size or a characteristic length. Step 5 involves aggregation of the set-based point clouds (Liu et al. 2021) to obtain the in-situ discrete fracture network represented by HSV colors.

Once the boundary discontinuities forming the blocks at a specific location (or within a homogeneous domain) are identified in Step 5, characteristics of discrete blocks can be determined. Step 6 includes two methods for evaluating the in-situ block system. The first involves estimating the mean volume and size distribution of the block system. The required inputs (Palmstrøm 1995 and Cai et al. 2004) are the set-based mean orientation, spacing and persistence ratio. The second method focuses on quantifying rock polyhedrals. This computation includes the location, shape and volume of a block, together with assessments of the kinematic removability, failure mode, and 3D limiting equilibrium condition of the block system based on Block Theory (Goodman & Shi 1985).

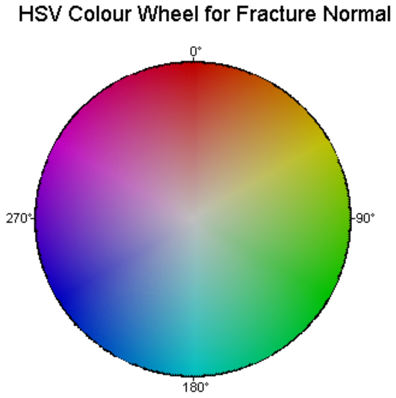

Figure 2. HSV-color wheel for 3D structural rendering.

3 APPLICATION EXAMPLES

3.1 Case 1 – Rock Slope

Figure 3a depicts a point cloud of a blocky rock outcrop beneath a castle in Austria. The slope has a length and height of approximately 250 m and 180 m, respectively. The mean attitude (dip direction/dip) of the outcrop is 099°/78°. To identify potentially unstable areas, the entire outcrop was scanned with a terrestrial laser scanner from five positions. The four white boxes in Fig. 3a show regions where block stability was assessed. While no indications of past block instability were detected within the upper regions (ST1:upper left; ST2: upper right), moulds of previous block failures are observable in the lower left (FR1) and lower right (FR2) regions.

The entire point cloud was evaluated using BLOCKinPCD. The HSV representation of the rock structure is shown in Fig. 3b. The pole diagram of the seven dominant joint sets identified is shown in Fig. 3c, and Fig. 3d depicts an example of digital joint spacing mapping conducted on the bedding set B within region FR1.

The joint set orientations are constant on the scale of the outcrop, but the set-based spacing and persistence have significant spatial variations. In regions FR1 and FR2, the joint set spacing is approximately 50% of the joint set spacing in the stable regions ST1 and ST2. Conversely, the joint set persistence within FR1 and FR2 is almost 100%, while the persistence within ST1 and ST2 is only about 30%. The higher degree of fracturing within FR1 and FR2 produce a mean block volume of 2.8 to 3.3 m^3, roughly one-third of the block volume in regions ST1 and ST2.

Fig.3e is an example of the output of BLOCKinPCD processing, which is the reconstruction of the past block failure (block mould) in FR1. Within FR1, the joint set J11 and J12 create the overall slope surface, sets J4 and J5 represent two steeply dipping joint sets that cut into the slope, and the bedding set B dips gently into the slope. The point cloud reveals that a portion of the slope within FR1 protrudes 1.8 meters from the average slope, resulting in the bedding (that dips into the average slope) becoming a localized free surface. This allows blocks cut by J4, J5, J11 and J12 to slide along J5.

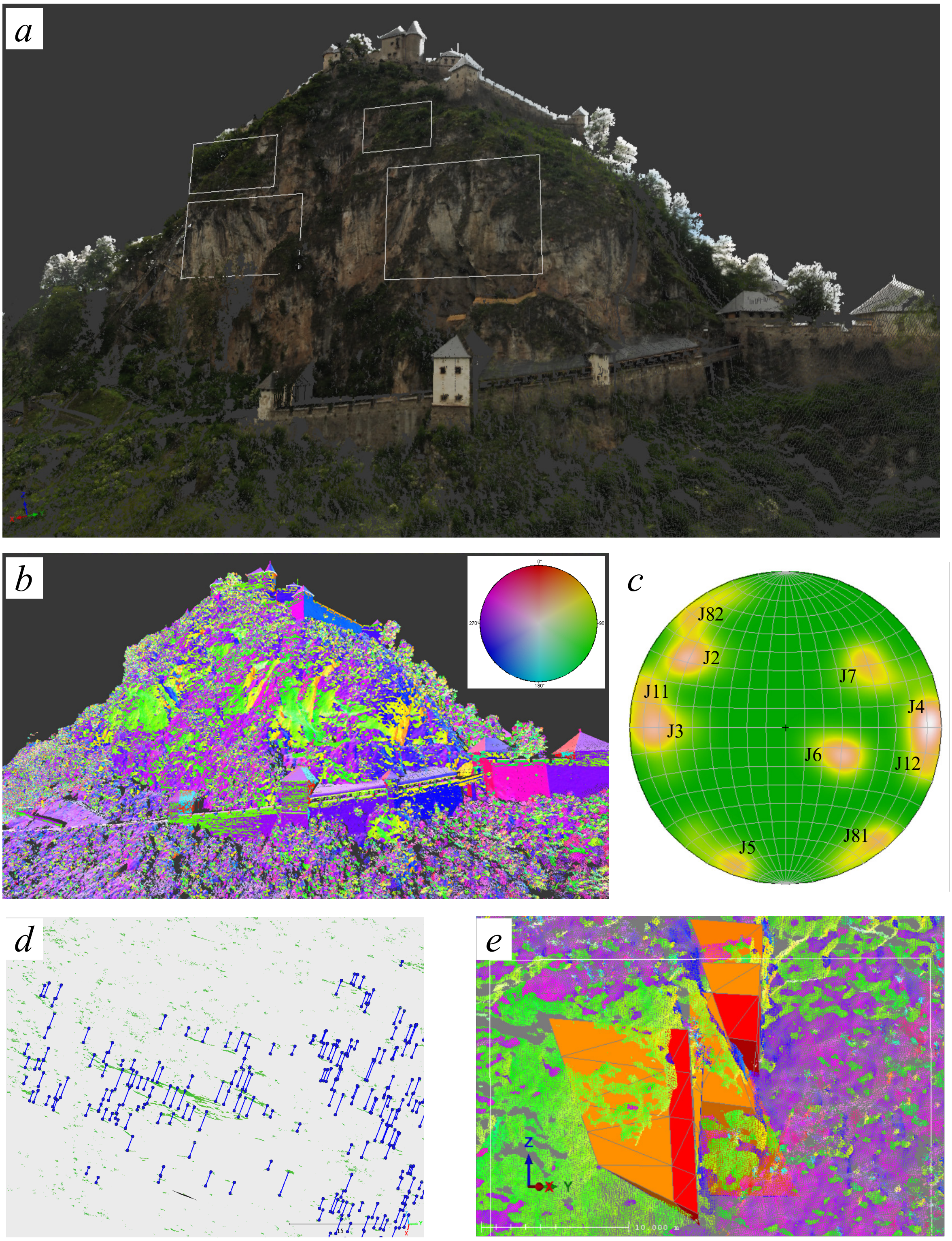

Figure 3. BLOCKinPCD for identifying in-situ block arrays and evaluating slope instability.

3.2 *Case 2 -Tunneling*

LiDAR point cloud data (Liu & Kieffer 2012) collected on 3D excavation surfaces in a 30-meter-long adit with a cross-sectional area of 2.3 m × 2.3 m is used to verify the applicability of BLOCKinPCD to tunnel excavations. Figure 4a shows the dominant orientations of the five discontinuity sets, including joint sets J1 through J4 and schistosity (SF). According to the classification of the influence of discontinuity orientation on tunnel excavation stability (e.g. Francis 1991), J1 through J4 are very unfavorable for the excavation direction of 87°/0° (bearing/plunge), while the flat-lying schistosity is categorized as unfavorable. However, as enumerated below the actual rock mass behavior during tunneling is also dependent on joint persistence.

As an illustrative example, two 10-meter long sections of the tunnel were selected to compare the results of the BLOCKinPCD processing. Although there is no substantial difference in the orientation and spacing of the five discontinuity sets within the two sections, the persistence of the sets in the first section ranges from about 33% to 42%. Fig.4b shows the persistence pattern of J1 and J2 within the first section. The rock mass in the first section exhibits only small and localized. In the second section, a single continuous fault zone (C5 of Fig. 4a) occurs and the discontinuity persistence (e.g. J1 & J2 in Fig.4d) ranges from about 51% to 79%. This results in significant overbreak along the northern wall and crown.

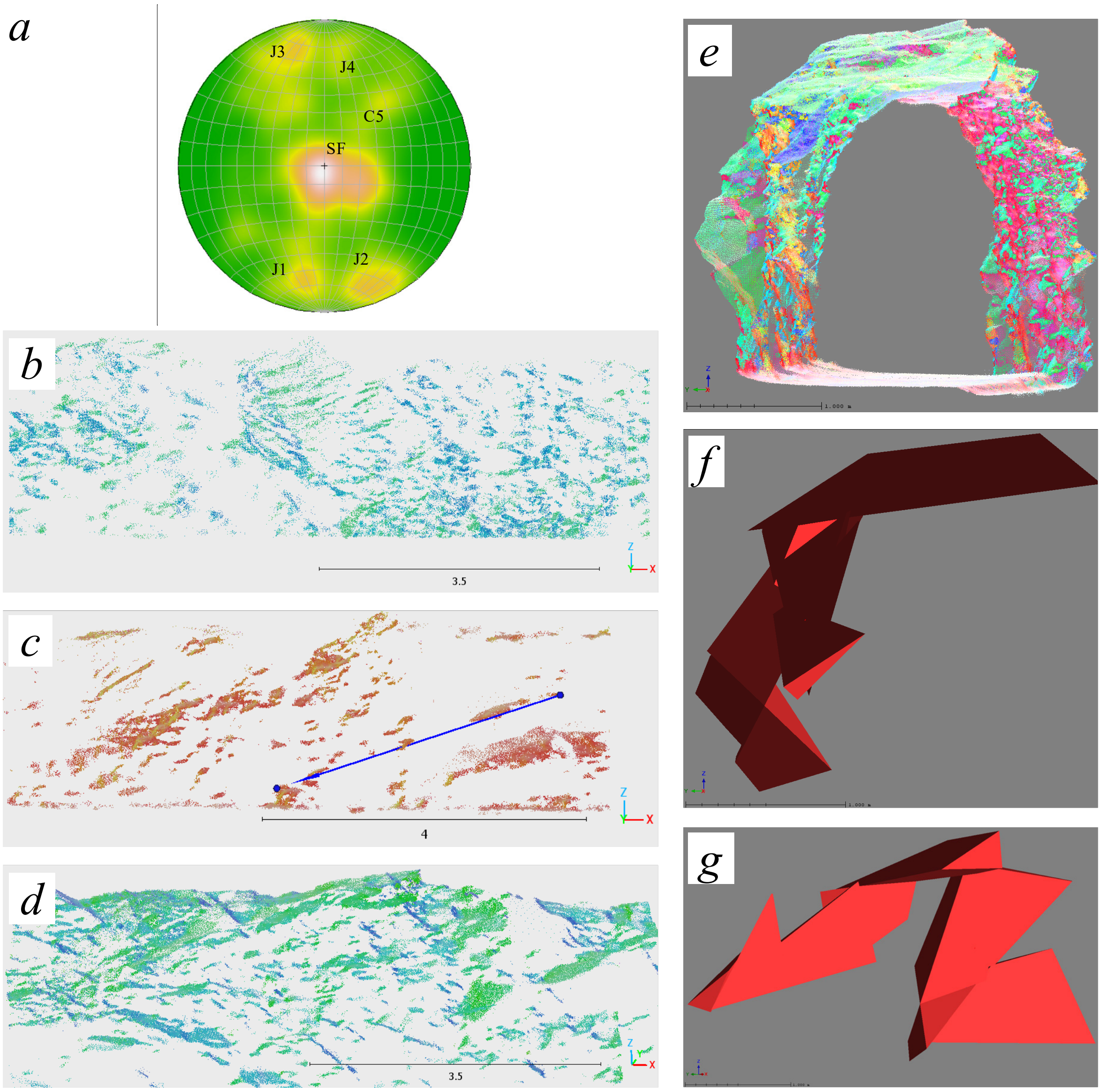

Figure 4. BLOCKinPCD in quantifying the change of rock structure during tunneling.

4 CONCLUSION

The applications of the BLOCKinPCD method to rock slope and tunnel engineering show that the remote measurement of the engineering geological outcrops and the digital data processing can quickly and effectively provide the relevant parameters of the 3D rock structure. Although this digital processing approach cannot replace the judgement of engineering geologists and rock engineers concerning the actual behavior of the rock mass during construction, BLOCKinPCD improves the objectivity and the quality of the engineering representation of the rock mass.

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