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Deterministic in-situ block size estimation using 3D terrestrial laser data

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ABSTRACT: A large amount of armourstone is needed for the construction of breakwaters that protect harbors. Sharp tender price and optimized design require an accurate prediction of the blast yield of quarries selected for the production of armourstone. The Blasted Block Size can only be smaller than the In-Situ Block Size. In practice, the IBS is estimated based on mean discontinuity orientation and spacing values derived from scanlines recorded manually. Instead, we propose a novel approach: the voxel method. The voxel approach uses all discontinuities visible in the rock face. The discontinuities are extracted from laser scanning of the quarry face. Blast induced fractures are discarded and discontinuities that have a similar orientation and a close spacing are merged assuming that they belong to the same discontinuity plane and were wrongly split during the segmentation process. The potential of our method is demonstrated for a quarry in Benin.

1 INTRODUCTION

A large amount of armourstone weighting from 500 kg to dozens of tons is needed for the construction of coastal structures that protect harbors and seawalls from waves or trap beach sand at holiday resorts. Quarries have to be selected for the production of heavy grading armourstone. By matching the expected quarry yield curve (i.e, tonnage of armourstone versus block size after blasting) to the demand for rock materials, the design of coastal structures can be optimized in order to reduce construction costs (Vrijling and Nooy van der Kolff, 1990).

A good estimation of the distribution of large blocks in blastpiles requires a model that uses as input parameter the In-Situ (or naturally occurring) Block Size distribution (IBSD) (Latham et al., 2006). Obviously, the Blasted Block Size cannot be greater than the In-Situ Block Size (IBS).

Simple methods have been developed to estimate the IBS distribution from the statistical analysis of scan line data recorded on 3D surface exposures (Wang et al., 1990) or 1D borehole logging data (Palmström, 2001 and Latham et al., 2006). These methods produce a rough estimation of the IBSD as they oversimply the rock mass by averaging spacing and orientation of discontinuities and assuming not more than three discontinuity sets or systematic jointing. The dissection method (Wang et al., 1991) reproduces the blocky rock mass without having to simulate the statistics of the discontinuity sets. It works with the intercept and orientation of discontinuities measured along directions that sample properly the rock mass structure. Thanks to its deterministic nature, the dissection method performs better than the Wang's equation or the Palmström and Latham's method. In this paper, we present a novel approach to estimate the IBS distribution that shares with the dissection method this advantage. Contrary to the dissection method, our method uses all discontinuities visible in the rock face.

After a brief presentation of the laser scanning technique and its application to rock mass characterisation, we explain our approach step by step. We demonstrate how it works with data recorded at the Dan quarry, a granite quarry dedicated to the production of armourstone in Benin. Then, we discuss the merits and shortcomings of our approach and propose ways to improve its predictive capacity.

2 LASER SCAN DATA ACQUISITION

This chapter describes how laser scanning was used to sample the geometry of the rock face of the Dan quarry in Benin. First the principle of laser scanning is shortly recalled, before the actual data acquisition at the quarry is described.

In the field, two zones were scanned. The East face of the quarry (Fig. 1) was scanned twice, once before blasting, once after blasting. The North West corner was scanned once. In this paper, we only exploit the set of laser data obtained on the East face after blasting.

Figure 1. East face of the Dan quarry after the blast. The face is about 10 m high. It is intersected by at three dominant discontinuity sets, two subvertical and one subhorizontal sets with a mean true spacing of 4.3, 0.5 and 1 m, respectively and a less dominant diagonal set.

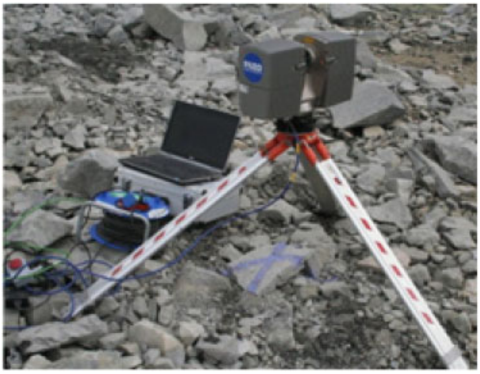

Figure 2. Pharo 120 laser scanner in the Dan quarry.

The combination of the different laser scanner data sets to correct for the limited persistence of discontinuities is out of the scope of this paper.

2.1 *Principle of laser scanning*

Laser scanning is based on the principle that when an electromagnetic light wave strikes an object it is either reflected, transmitted or absorbed. When the laser scanner emits a laser beam on the center of a rotating mirror, the laser beam deflects and travels to a distant object in a certain direction. This known direction is recorded and parameterized by two angles, with respect to a horizontal and vertical reference line through the scanners optical center respectively. After hitting this object a portion of the emitted laser beam is reflected back to the laser scanner. The travel time of the laser beam directly translates in the range distance between scanner and object (Vosselman and Maas, 2010). Next to the distance, also the intensity of the returned laser pulse is recorded. The darker a point, the less reflective the surface of incidence (Large and Heritage, 2009). In this research we used a static panoramic laser scanner (Fig. 2), that is a laser scanner that operates from a fixed position and measures range distances to all objects in the spherical surrounding of the scanner. The result of one scan is a 3D point cloud whose coordinate center is at the scanner location.

2.2 *Point cloud registration*

In general, several scans for different locations are needed to fully sample an object. In our case five scans were required to fully sample the E-face of the quarry (Figs 1 and 3). The combination of different scans, each centered around its scan location, into a common point cloud is a procedure referred to as registration (Vosselman and Maas, 2010). The five scan locations are indicated in Figure 3 by red circles. Registration of two scans requires the estimation of transformation parameters, describing both 3D translation and rotation that transforms the second scan into the coordinate system of the first scan. Figure 3 shows the point cloud obtained after registrating five scans into a common coordinate system. A processing step such as registration always induces some errors. These errors come on top of measurement errors that depend on instrument, ambient conditions and measurement geometry (Soudarissanane et al., 2011).

At each of the 5 positions, the scan was recorded at a quarter of the maximal possible resolution. Each individual scan consists of about 41 million scan points. Registration resulted in one point cloud of 206 million points.

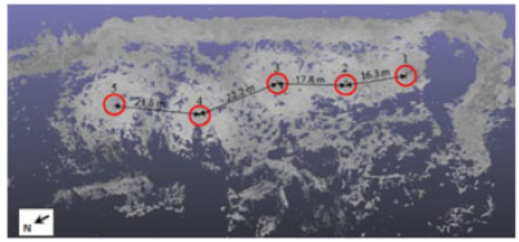

Figure 3. Top view of the scans of the East face after the blast. The scan positions are indicated by red circles.

3 FROM LASER DATA TO PLANE EQUATIONS

Next, the registered data set is segmented. The goal of the segmentation is to derive equations for the planes corresponding to the discontinuity planes as illustrated in Figure 4. According to Rabbani et al. (2006) segmentation is the process of labelling each measurement in a point cloud so that the points belonging to the same surface or region are given the same label. In Figure 4 for example, all point belonging to the red plane should become the same label. Several approaches exist; we followed the approach described in Vosselman and Klein (2010) and Slob (2010) in which an initial plane, a seed surface, is systematically extended by adding points, as long as an additional point is sufficiently close to the planar segment under construction. The segmentation algorithm applied in this research is managed by several parameters controlling i) neighborhood selection: which and how much close by points should be used to estimate local flatness; ii) seed selection: how to initialize a new planar region, and, iii) surface growing: under what conditions can additional points participate in a segment under construction. A resulting segmentation is shown in Figure 5.

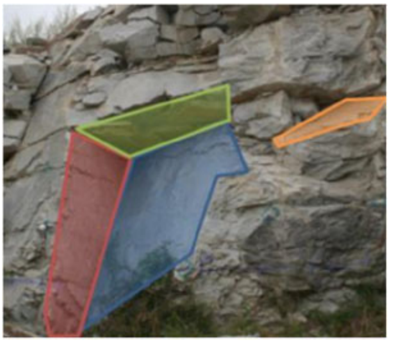

Figure 4. Discontinuity planes corresponding to rock faces.

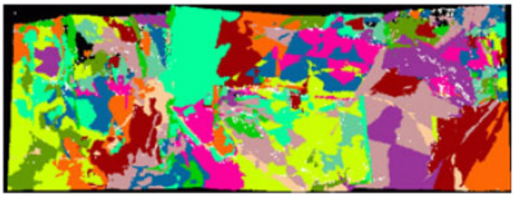

Figure 5. Segmentation result showing 159 segments.

Ideally, each resulting segment contains exactly all scan points sampling a rock face. In practice, however, a segmentation suffers from local over- and under-segmentation which means in this context that points sampling the same rock face end up in different segments, or, that different rock faces join in one segment. These effects are difficult to avoid, as the point density and noise levels are varying throughout a point cloud but are also influencing the segmentation results. Assuming a segment is well-representing a rock face, a plane equation describing location and orientation of the rock face is estimated by least squares from all individual points in the segment at hand.

Next to the laser scanner survey, traditional scan lines were recorded manually and compared to virtual scan lines extracted from the laser scanner data set. The comparison allows validating the segmentation of the point cloud.

4 VOXEL METHOD FOR IBSD ESTIMATION

In this chapter it is described how a segmentation of a point cloud sampling a rock face can be used to obtain an estimation of the in situ block size distribution using the voxel method.

4.1 *Bounding planes*

The segmentation results in a number of planar equations, each corresponding to one segment. If some amount of persistence is assumed, for example at least as far as the area affected by the blast, we arrive in the situation as illustrated in Figure 6. The black lines on the outside of the block are the intersections of the segment planes with this block. The green facets are located at the rock face, so all points behind the green facets are inside the rocks, while the area in front of the green facets is in fact the open space inside the quarry.

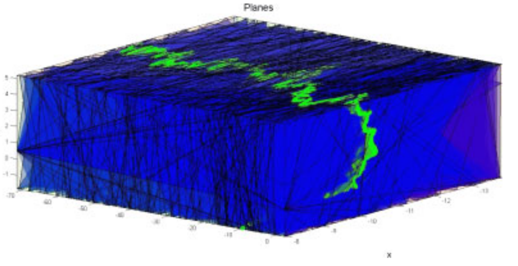

Figure 6. Discontinuity planes corresponding to rock face segments.

Some given point $p = (x, y, z)$ inside the rocks is therefore surrounded by planes. For each plane it can be determined if p is above or below that plane, assuming no plane is exactly horizontal. This is done by writing the plane equation in determinant form D(x, y, z).

$$D(x, y, z) = \begin{vmatrix} x - x_1 & y - y_1 & z - z_1 \\ x - x_2 & y - y_2 & z - z_2 \\ x - x_3 & y - y_3 & z - z_3 \end{vmatrix} \quad (1)$$

where $(x_i, y_i, z_i), i = 1 \ldots 3$, denote three points that fix the plane (Lay, 2003). The value of D(x, y, z) is zero only if p is on the plane, while the sign D(p) differs from D(q) if p and q are on different sides of the plane.

4.2 *Voxel evaluation*

The persistency assumption allows us now to define a block as all the points in the rock that are exactly above or below the planes. Another assumption that is made here is that all discontinuity planes have been indeed detected. In the following we do not evaluate for all points in the rock if they are in the same block, but only for a limited set of so-called voxel centers. A voxel is the 3D equivalent of a pixel. We consider our rock as a union of a number of voxels, and want to assign each voxel to a block. If successful, we can approximate the volume of the block by simply adding the standard volumes of all voxels assigned to the block.

This is illustrated in 2D in Figure 7. The green points denote the voxel centers that decompose a rock intersected by discontinuity planes A, B, C and D. Apparently, voxel centers 5 and 9 belong to the same block, and as there are no other voxel centers belonging to that block, the volume of the block is estimated as 2V with V the volume of one voxel. Using Equation 1 the assignment of voxels to blocks is automatized by a) determining for each voxel center its so-called discontinuity code, and b) grouping all voxels with the same code. The discontinuity code of a voxel center is simply the ordered sequence of matrix signs

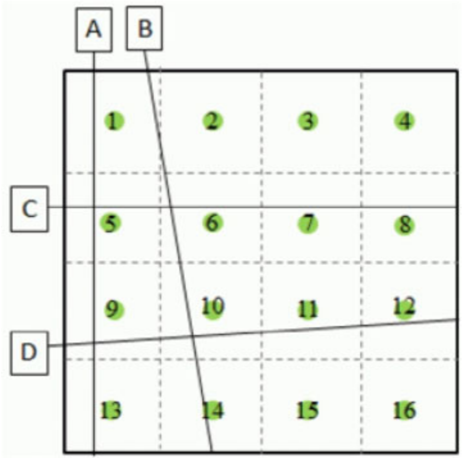

Figure 7. Assigning a planar code to a voxel.

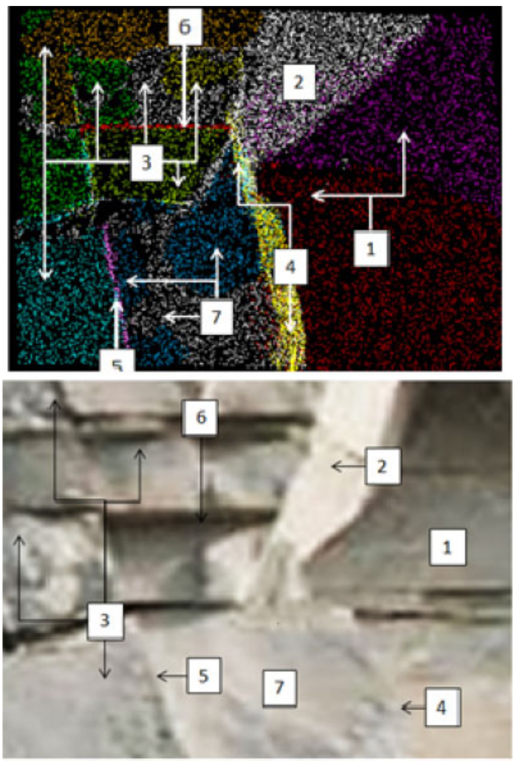

Figure 8. Merging of discontinuity faces that belong to the same (rough) discontinuity plane.

as obtained by Equation 1 for each of the planes A, B, C and D. For example, the code of point 9 could be $c_9 = +-+-$, while the code of point 13 equals $c_{13} = +-++$, as point 13 is on the other side of line D. The code of point 5 however is again $c_5 = + - + -$, so $c_5 = c_9$, and therefore voxels 5 and 9 belong to the same block.

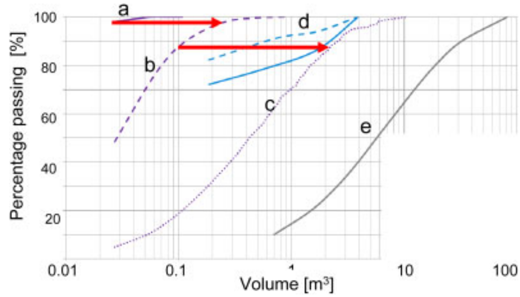

Figure 9. Percentage passing sieve (%) versus Volume (m^3). Comparison of IBSD produced with the voxel method (a) using all equation planes derived from the point cloud segmentation, (b) after elimination of small discontinuity faces, (c) and merging of discontinuity faces belonging to the same plane with (d) measured BBSD and (e) IBSD predicted using the Wang's equation method applied to the scan line data measured at the bottom of the face.

4.3 *Reduction of number of discontinuity planes*

Blasted blocks that were measured in the quarry were found to be coarser than the naturally occurring blocks produced by the Voxel method. The underestimation of the IBS by the voxel method results partly from the assumption that all discontinuities are persistent over the whole blasted volume, even the small fractures caused by blasting. It is also related to the non perfectly planar geometry of the discontinuities that daylight at multiple locations on the rock face. By eliminating small discontinuity faces and merging faces that are sub-parallel and at a close spacing (Fig. 8), we produced with the Voxel method a more realistic IBSD (Fig. 9).

5 CONCLUSIONS AND RECOMMENDATIONS

The voxel approach is a novel approach that can be used to estimate the size of blocks formed by discontinuities that are visible on a rock face and are assumed to persist over the whole depth of the blasted volume. It is explained step by step in the paper. It presents the advantage of using all discontinuities that are visible in the rock face, rather than only those measured along scan lines positioned at the bottom of the face. The discontinuities are extracted from point clouds that are collected during laser scanning of the quarry face. Our first application of the voxel method to a granite quarry in Benin showed that it is necessary to filter the discontinuities derived from the automatic segmentation process in order to avoid an underestimation of the IBSD. We obtained more realistic predictions of the IBSD after having discarded small blast induced fractures and merged discontinuities that have a similar orientation and a close spacing, assuming that they belong to the same discontinuity plane and were wrongly split during the segmentation process. Next, we plan to combine scans recorded before and after blast and scans acquired on perpendicular faces to take into account, in a deterministic way, the discontinuity persistence in our estimation of the IBSD.

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