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APPLICATION OF TERRESTRIAL LASER SCANNING FOR THE GEOMETRIC CHARACTERIZATION OF DISCONTINUITIES IN LIMESTONE QUARRY FACES

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Abstract. This work investigates the effect of Terrestrial Laser Scanning (TLS) configuration on measuring the geometric properties that characterize discontinuities in limestone quarry faces. While the application of laser scanning technologies to acquire the 3D geometry of quarries is well established, the extent of differences in acquired parameter values that depend on the equipment's parametrization is usually overlooked. We provide a discussion of the quantitative evaluation of discontinuity parameters (dip direction, dip angle, aperture, spacing, persistence, roughness, and deepness) based on the configuration of the TLS device (resolution, accuracy, and quality) and its application on a limestone quarry case study. Data from the case study show that not all discontinuity parameters need the same point cloud density. Spacing and dip/dip direction are highly consistent across the different point clouds, while aperture and persistence show greater sensitivity to resolution and scan position.

Keywords: terrestrial laser scanning, LiDAR, discontinuities, geometric characterization, limestone quarry, point cloud.

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1. Introduction

Geological structures strongly influence the complex mechanical behavior of a rock mass. An important aspect concerning its evaluation is the geometrical characterization of discontinuities (Cacciari & Futai, 2016). It is essential to determine the geometric characteristics of the discontinuities to evaluate the stability of the bench slope on open pits, since they are considered, together with the mechanical characteristics of the rocks, as descriptors of the quality of the rock mass. Definitions of what constitutes a discontinuity vary widely among geologists and engineers, as well as across international standards (Zhang, 2017). Discontinuity is the collective term used for any surface that introduces a break in rock continuity. Therefore, discontinuities are bedding planes, faults, dykes, joints, veins, and all the surfaces that represent a separation in the intact rock (Brady & Brown, 2007). The International Society for Rock Mechanics [ISRM] (1978) defines discontinuity as the generic term for mechanical fractures in a rock mass that has zero or low tensile strength. The American Society for Testing Materials' definition of structural discontinuities incorporates features with considerably greater strength, including cleavage and bedding (Hencher & Richards, 2015).

The presence of discontinuities depends on rock mass lithology, weathering degree, excavation method, and several other factors (Schultz, 2019). The discontinuities influence the rock mass behavior, as they introduce anisotropy in deformation, strength, and permeability properties (Lisjak et al., 2014). The quality of ornamental stone depends on the persistence and color veins, among other aspects (Ashmole & Motloung, 2008). Therefore, monitoring discontinuities is imperative in quarry management. For this, it is usual to carry out field surveys using methods such as scanline or window mapping. Their success depends on access to the sites and the experience of the technician who carries out the survey. In addition to these aspects, the quality of the survey data in mining projects can be compromised if not updated frequently, as mining extraction leads to the decompression of the working faces, changing the aperture and the persistence of discontinuities. Persistence is responsible for the geometry of potential slip surfaces.

A wide range of possibilities in spatial data acquisition has appeared with Terrestrial Laser Scanning (TLS), a technology that has proven its applicability in various fields from archaeology to architecture and civil engineering, including change detection and deformation monitoring (Mukupa et al., 2015), and also in the characterization of discontinuities in quarry faces (Deliormanli et al., 2014). TLS, also referred to as terrestrial LiDAR (light detection and ranging), is a data acquisition technique that acquires dense point clouds, i.e., the 3-dimensional coordinates of a very large number of points in direct view from the device, using laser pulses and measuring the device-to-target distances (Vosselman & Maas, 2010). Laser scanners can be operated when installed on aerial vehicles, satellites, or directly on a tripod. All laser scanners work on a similar principle: the measurement of the distance between the device and the target object or area via laser beams. This is possible thanks to measuring and recording the time that elapses from the moment the laser beam is sent to its return to the detector after reflection from the target surface. The known value of the speed of the propagating electromagnetic wave and the measured time make it possible to calculate the distance of the object from the scanner (Gu & Xie, 2013). The output of the survey with a TLS is a highly dense point cloud where each 3D point has assigned not only the reflected laser intensity value but also the color attributes obtained by photo draping.

Some of the advantages presented by TLS include the capture of physically inaccessible points (due to the use of a laser wavelength, the signal is returned by the surface of scanned objects in direct line of sight from a scan station), the high level of geometric/positional detail and precision, the possibility to revisit the model, and the georeferencing of the scene using a predefined coordinate system. On the other hand, the process also demands consideration regarding the scan position network and the overall geometry of the site, the data capture parameters (quality and accuracy), the dependence on weather conditions during data capture, the existence of reflective, transparent, and dark surfaces, the high 3D point cloud data volume, and the processing of the raw captured data.

To obtain a comprehensive 3D point cloud, it is often necessary to combine several point clouds resulting from individual scan stations, with distinct fields of view. The goal for the proper creation of the point cloud is to align and merge the separate data and obtain a coherent set of points in a single coordinate system. This is achieved either by the establishment of the coordinates of tie points (usually marked with topographic targets) or by identifying features such as plans or surfaces (Tang et al., 2010; Bhatla et al., 2012). Special attention must be paid to the planning of the fieldwork, as an insufficient number of identified features may affect the combination of scan stations, leading to rigid deformations (translations, rotations) between scans.

After the creation of a single 3D point cloud, it is necessary to process the data to remove outliers and reduce noise. Depending on the size of the point cloud, it may be necessary to divide it into smaller key parts, which may be processed in parallel to optimize computing time. Concerning the outliers, most approaches use local statistics of geometric properties of the cloud to define outlying factors, such as local density, distance to nearest neighbors, or eigenvalues of the local covariance matrix (Pătrăucean et al., 2015). Some options are the establishment of a hard threshold and the use of a global distribution to identify diverging points from the expected distribution of the cloud elements. In addition, the temporal artefact outliers, caused by changes in the scene during the capturing process, such as the movement of objects or persons, require inspection and correction. Similarly, to the removal of outlier elements from the point clouds, and depending on the purpose of the survey, noise filtering techniques, which analyze the local neighborhood of each scanned point and execute a smoothing operation, could be employed to remove excessive detail and correct the effects of reflection during data capture. If needed, this operation should be executed, attending to the risks of over-smoothing of sharp local features, resulting in the elimination of relevant data. To this end, several resources can be used, such as kernel density estimation, the iterative down-sampling upsampling strategy, and the anisotropic filtering (Lange & Polthier, 2005).

In this paper, we explore the applicability of TLS as a data acquisition technique for the morphological and geostructural characterization of discontinuities, extracting several of their properties from the obtained point cloud, namely dip direction, dip angle, aperture, spacing, persistence, roughness, and deepness. A discussion on the influence of the selection of parameters during spatial data acquisition and the TLS-object geometry in such characterization is included. A case study using the acquisition of the geometry of a limestone quarry using TLS was conducted. The quarry is located near the city of Fátima, Portugal, located in the Maciço Calcário Estremenho limestone region, close to the Serras de Aire and Candeeiros Nature Park.

2. Background on discontinuities and geometrical data acquisition

2.1. Morphological and geostructural characterization

The term *discontinuity* is used as the general term for a mechanical break or plane of weakness in rock mass, such as joints, bedding planes, fractures, faults, veins, and foliation planes (Zhang, 2017). The most common and geotechnically significant structural features for rock engineering design are joints, which display fracture surfaces in the rock with no visible displacement. Another type of systematic discontinuities found in sedimentary rocks, called bedding planes, separate layers with different compositions. Veins, also described as cemented joints, are mineral infillings of joints or other fractures.

Shear strength of discontinuities is an important rock parameter and requires the determination of fundamental frictional parameters together with characterization and quantification of geological factors such as surface roughness, persistence, aperture, dip angle and dip direction, spacing, and the extent of infill for the discontinuity in situ (Hencher & Richards, 2015). The shear strength of discontinuities is one to two orders of magnitude less than that of intact rocks. Thus, the characteristics of discontinuities play an important role in the deformation and destruction of rock masses (Zhang et al., 2020). The mobilization of the discontinuities' shear strength introduces instability on the bench slope, triggering block movements. At the bench scale, the main type of instability is planar or wedge failure. The block size that is kinematically available to move is determined by the discontinuities' persistence, roughness, and aperture.

The Commission on Standardization of Laboratory and Field Tests of the International Society for Rock Mechanics has suggested methods for the quantitative description of discontinuities in rock masses (ISRM, 1978). Among the many geometrical properties, the morphological and geostructural characterization of discontinuities can be made through the identification of the following (Figure 1):

- Dip angle and dip direction – describe the position of the steepest line relative to the horizontal plane, and the azimuth with the North direction, respectively;
- Aperture – describes the distance between the two borders defined by the discontinuity;
- Roughness – describes the surface unevenness and waviness of the discontinuity relative to its mean plane;
- Persistence – describes the length of the discontinuity;
- Spacing – describes the distances between adjacent discontinuities.

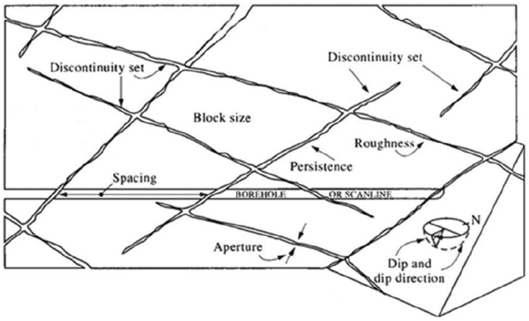

Figure 1. Schematic of the geometrical properties of discontinuities in rock (adapted Hudson & Harrison, 1997)

The properties of discontinuities must be included in the geotechnical model to recognize potential slope failure mechanisms. Determining the spatial distribution of structural discontinuities is of utmost importance, also for the design of work plans and the subsequent exploitation of quarries, so knowledge of the main discontinuities has a key role in optimizing the extraction process (Zanzi et al., 2017). Moreover, the identification of weakness zones could assist in the calculation of reserves and design of the advance faces of a quarry, which would reduce extraction costs (Rey et al., 2015).

2.2. Acquisition techniques for geological structures data

For the identification and mapping of discontinuities, there are diverse techniques. Manual field survey methods, used to characterize discontinuities, produce large errors due to difficulties in obtaining samples and presenting safety risks (Kemeny & Post, 2003). The solutions that are mostly used present some disadvantages, such as the time-consuming process of acquisition in the case of surveying with total stations, the difficulty of obtaining data from hard-to-reach places when compass and inclinometer are used, or the time-consuming preparation and processing of photogrammetry-based methods relying on the conjugation of matching geometries (Ashmole & Motloung, 2008). Several direct and indirect methods can be used for the data acquisition required to characterize the discontinuities. Fisher et al. (2014) compare discontinuity geometrical data obtained on an abandoned quarry from a direct measurement using the transit compass method (specifically in collecting discontinuity orientation data) to indirectly obtained terrestrial LiDAR measurements. The results of the study show that both data sets can identify discontinuities in the rock mass. Authors extend the discussion to the factors that may cause differences between the transit compass and LiDAR datasets in the characterization of geometrical discontinuities, namely the existence of shadow zones, and the spatial variation of discontinuity orientations.

The laser scanning technology has a wide range of possible applications in quarries, either installed on a tripod, on a handheld device, or mounted on an aerial platform, such as UAVs. It can be applied to monitoring high face slopes, an important task to ensure safe mining. Long et al. (2018) present measurements in quarries located in Vietnam and Poland, by using laser scanner technology. The objective of the work was to investigate mesh algorithms, which can be used to interpolate 3D models of pit walls. The laser scanning gives information about all measured objects, not only the chosen control points. Thus, based on the obtained results, it can be concluded that the presented approach by Long et al. (2018) may be an alternative to the conventional methods, giving more complete and accurate data about the observed object (Long et al., 2018). Mastrorocco et al. (2018) show how point cloud data from laser scanning and high-quality images can be combined to map deterministically and characterize rock surface discontinuities to create accurate models to indirectly measure their geometric characteristics. In their case study, comparisons between traditional methods and point cloud datasets have been made. Authors also enumerate and discuss the sources of errors in the dataset (e.g., scan referencing, the horizontal and vertical accuracies of the scanning device, or the distance to the scanned surface) that may affect measurements of discontinuities in virtual environments.

More recently, several studies have emphasized the application of automated and semi-automated algorithms to detect and classify discontinuity surfaces from TLS point clouds, as the technology evolution has raised the difficulty of effectively processing large point cloud datasets. Within this scope, methods range from region-growing segmentation and multipass partitioning to multilevel classification strategies that extract planar patches, orientations, and sets for statistical analysis. Ma et al. (2024) proposed a classification strategy to identify discontinuities using point clouds over complex rock surfaces. Data was processed with machine learning algorithms to categorize the acquired points distributed on an exposed rock mass at a road cut slope into several discontinuity categories. Cao et al. (2025) applied a method that integrates multiple algorithms to achieve accurate point cloud pre-segmentation and comprehensive discontinuity characterization. The method involves a point cloud feature estimation step, where true 3D methods and surface curvature are considered, followed by a pre-segmentation to ensure that each segmented cluster represents a single, individual discontinuity. This enables the measurement of each isolated discontinuity over its defining cluster of 3D points, via analytic geometry (for dip and dip direction, trace length, and spacing). Results were very positive: a high accuracy in dip direction measurement was observed in comparison to reference orientations.

3. Materials and methods

3.1. General methodology

A general application of TLS to the identification and characterization of discontinuities in quarries requires preparing the survey by selecting scan positions that cover the area of interest, combined with the parametrization of the equipment. The resulting raw data, in point-cloud format, needs to be registered to a single coordinate system to provide a coherent, complete geometric dataset. It is then possible to use this global model to identify and characterize the local discontinuities (Figure 2).

During the survey preparation stage, it is necessary to establish a network of scan station positions relative to each other and to the surveyed area, to ensure a complete view of it and an adequate distance between the TLS and the quarry façades. In each of these scan positions, a parametrization of the TLS equipment allows the surveyor to configure the scanning process in terms of resolution (density of surveyed points at a specified distance), field of view (angular extension for both horizontal and vertical axes), quality (number of emitted pulses per point), and colour mode (properties relative to the colour acquisition).

After the fieldwork acquisition of spatial data, a registration procedure allows creating a digital model supported by a point cloud that combines the points obtained in each scan position. Then, outlier points resulting from the noise inherent to laser-scanning acquisition-related, e.g., to the environment and local conditions, have to be removed.

The third stage uses the obtained digital model of the quarry to identify joints and veins, and then their characterizing properties on a data processing software capable of adding features such as lines and planes, and measuring their geometrical properties. Dip angle and dip direction are obtained through the measurement of the relative position of a plane that fits the discontinuity, from which slope and aspect can be directly obtained (Figure 3a). Aperture is estimated by measuring the spacing between the borders at several levels (Figure 3b). Roughness, which is applied only for structural discontinuities (joints), is

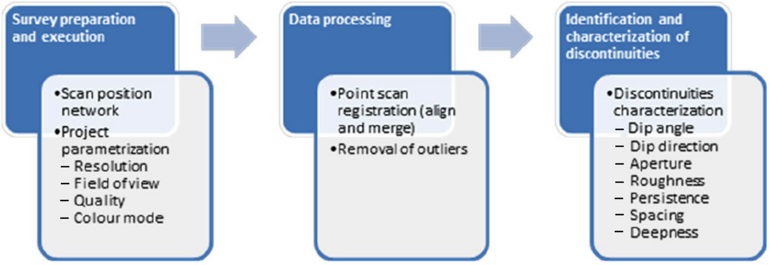

Figure 2. General workflow for TLS-based characterization of discontinuities in quarries

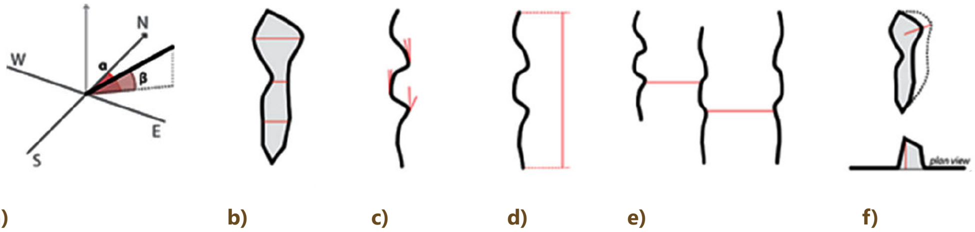

Figure 3. Diagram of geometric properties characterizing discontinuities: a) dip direction (a) and dip angle (b); b) aperture; c) roughness; d) persistence; e) spacing; f) deepness

estimated by measuring the angles defined by regularly spaced tangents to the borders and the average line of the discontinuity (Figure 3c). Persistence is estimated by the length defined by the extremities of the discontinuity (Figure 3d). Spacing is obtained by measuring the perpendicular distances between successive discontinuities of the same family (Figure 3e). Deepness, which applies only to hollow veins, is the distance measured between the façade plane and the farthest point inside the discontinuity (Figure 3f), and was added to the set of geometrical properties due to the capacity of TLS to acquire points inside the discontinuities.

3.2. Location and geology of the case study

The presented methodology was applied to a section of a limestone quarry in Casal Farto, 8 km to the southeast of Fátima, in the Santarém district, Portugal, an area included in the Serras de Aire and Candeeiros Nature Park. Figure 4 shows the location of the quarry.

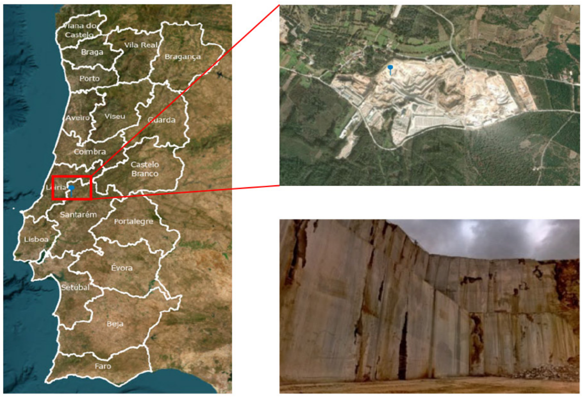

Figure 4. Location of the quarry in Mainland Portugal (left); aerial view of the quarry, with location of the scanned façades (top right); view of the study area (bottom right)

The area where the surveys were performed is located on the surface fold of limestone, related to the sedimentary types of rocks from the Carboniferous era. The type of limestone that exists in the excavation region is the "Creme Fátima". Its colour is a light beige with thin to medium grain. Some of the occasional thin lines and some darker brown spots were visible. The minerals that are present in the limestone are mainly calcite and aragonite.

3.3. Survey preparation and execution

The equipment used to execute the survey was a Faro Focus 70 terrestrial laser scanner (Figure 5, left). The laser has a ±1mm resolution at a 70 m distance. The scanner can cover a 360° x 305° field of view (Faro, n.d.). Figure 5 (center) shows the device near the surveyed quarry faces during data acquisition. This device enables the detailed measurement and documentation of large object spaces and buildings, and is perfectly suitable for short-term measurements up to 70 m. The speed of the laser scanner used during testing reaches up to 976,000 points per second, and its range is up to 350 m. The device also records the angle at which the laser beam is sent. The device used in the measurements can cover a 360° horizontal plane and approximately 330° vertical plane (does not cover angles near the nadir as it is out of the field of view). The measured time and the beam deflection angle allow the determination of a point cloud with local 3D coordinates, which can be converted into a real-world coordinate reference system.

In this work, two different configurations and scan stations of the TLS were used to obtain the geometrical characterization of a limestone quarry section. Two scanning definitions were considered, one for each scan position. The first definition used a 6.1 mm at 10 m distance resolution, while the second was set at 3.1 mm at 10 m. The two scan positions for the TLS equipment were selected to ensure the full coverage of the quarry façades – SW, NW, and NE (Figure 5, right). As both scan positions had a full field of view over the façades, only one configuration was tested in each. In both scans, four measurements were taken for each point in the façade to increase the positional quality. Each of these scans originated a point cloud, respectively named PC1 and PC2, without the need to combine multiple scan locations. Also, high-resolution photos were acquired, enabling the capture of radiometric values for the points in the clouds.

3.4. Data processing

ReCap Pro software was used to merge both point clouds into a single cloud with a higher density of points. Key points supporting this operation were selected from the cut stone blocks lying on the site. Statistics provided by the software, namely balance, overlap area, and number

Figure 5. FARO Laser Scanner S70 (left); equipment during data acquisition (center); the façades viewed over a base map from Google Maps (google.com/maps)

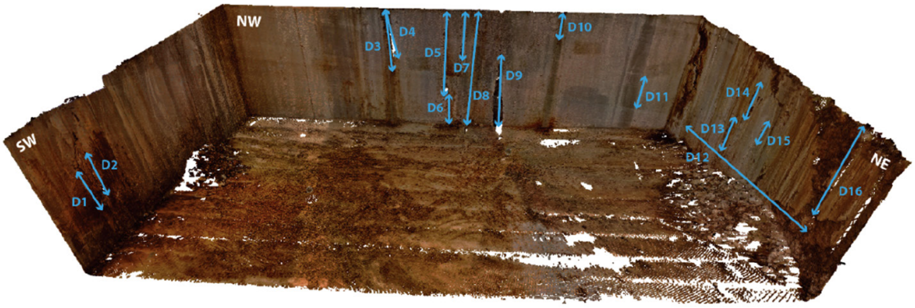

Figure 6. A point cloud (PC3) and the identified discontinuities in the three façades

of points closer than a pre-determined distance, were analyzed and deemed satisfactory. In this third point cloud, onwards named PC3, the point-to-nearest-point distance was at most 6 mm for 97.4% of the input points. For the subsequent analyses, the three-point clouds were used as a basis to map and characterize discontinuities. For each of the three-point clouds, a data cleaning process enabled the removal of outliers and irrelevant points.

3.5. Identification and characterization of discontinuities

CloudCompare software was used to map discontinuities and support their characterization in terms of dimensions, directions, and angles. For that, planes corresponding to the discontinuities were drawn manually, perpendicularly to the planes of the façades. A total of 16 discontinuities in the three façades were manually identified in each of the three-point clouds. Figure 6 shows point cloud PC3, where the façades and the identified discontinuities are visible: on the SW façade, two discontinuities were marked – D1 and D2; on the NW façade, discontinuities from D3 to D11 were identified, and on the NE façade, five discontinuities, D12 to D16, were mapped.

Table 1. Results of the dip directions and dip angle in discontinuities

Discontinuity	Façade	Dip direction (°)			Dip angle (°)		
		PC1	PC2	PC3	PC1	PC2	PC3
D1	SW	221	220	220	89	90	87
D2		228	226	226	86	90	87
D3	NW	307	310	309	87	85	87
D4		308	308	308	87	84	81
D5		305	306	305	88	88	88
D6		311	311	311	89	89	90
D7		313	312	313	90	90	88
D8		303	305	306	85	86	87
D9		315	315	315	88	88	89
D10		304	306	305	88	86	90
D11		310	310	310	90	90	90
D12	NE	45	45	45	5	5	5
D13		40	42	42	88	88	89
D14		41	43	41	88	87	87
D15		37	39	37	89	90	90
D16		43	45	43	87	86	89

The geometry of the three-point clouds enabled the extraction of values to characterize the sixteen identified discontinuities through a set of descriptive parameters. These were dip direction, dip angle, aperture, roughness, persistence, spacing, and deepness. In general, there is no significant difference in dip direction and dip angle values between the three-point clouds. This is probably due to the characterization being made using a plane based on a generalized shape of the discontinuities (Table 1).

As discontinuities can be very irregular, an advantage of the digitization of its shape is the ability to support several geometric measurements and better characterize the aperture parameter. Measures were taken at one-third, half, and two-thirds of the extension of each discontinuity (Table 2).

Table 2. Measured values of aperture for the identified discontinuities

Discontinuity	Aperture (cm)								
	PC1			PC2			PC3		
	At 1/3	At 1/2	At 2/3	At 1/3	At 1/2	At 2/3	At 1/3	At 1/2	At 2/3
D1	3	2	2	4	2	3	3	3	2
D2	4	11	9	5	11	8	3	12	8
D3	7	7	11	8	7	10	9	6	11
D4	12	19	36	13	16	35	11	17	40
D5	18	18	32	19	17	33	21	18	35
D6	4	12	30	5	14	30	5	14	31
D7	6	11	34	7	9	32	8	10	36
D8	2	2	2	1	2	3	2	3	2
D9	5	61	119	6	72	122	5	69	124
D10	11	33	4	12	32	6	12	32	6
D11	5	4	4	4	2	1	6	3	2
D12	9	7	21	9	6	24	9	6	19
D13	13	37	26	15	36	26	13	36	24
D14	6	29	14	8	25	15	8	26	15
D15	9	11	8	6	13	7	9	11	6
D16	22	24	20	23	22	25	21	23	19

The characterization of aperture demands a good network of scan positions that provides a full field of view, in line with the increasing complexity of the boundary of the discontinuities. Measurements of roughness in the point cloud PC3 are presented in Figure 7. Roughness is only applied in the characterization of structural discontinuities. In the test case, only D1 and D8 were measured. Measurements were taken with a 1.0 m interval.

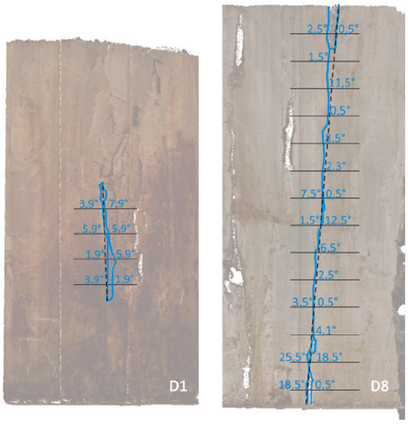

Figure 7. Measurements of roughness in discontinuities D1 (left) and D8 (right) using point cloud PC3

Persistence was obtained by measuring the extent of the plane segments (Table 3). As persistence depends on the identification of the extreme points of the discontinuities, and these are dependent on the parameters of the point cloud, differences are noticeable between scans. An example is given in Figure 8 for the D10 case.

Table 3. Measured values of persistence for the identified discontinuities

Discontinuity	Façade	Persistence (m)		
		PC1	PC2	PC3
D1	SW	221	220	220
D2		228	226	226
D3	NW	307	310	309
D4		308	308	308
D5		305	306	305
D6		311	311	311
D7		313	312	313
D8		303	305	306
D9		315	315	315
D10		304	306	305
D11		310	310	310
D12	NE	45	45	45
D13		40	42	42
D14		41	43	41
D15		37	39	37
D16		43	45	43

To obtain the spacing parameter, the "Point picking" tool from CloudCompare was used. The distance between discontinuities was measured at the same height. Table 4 shows the obtained values.

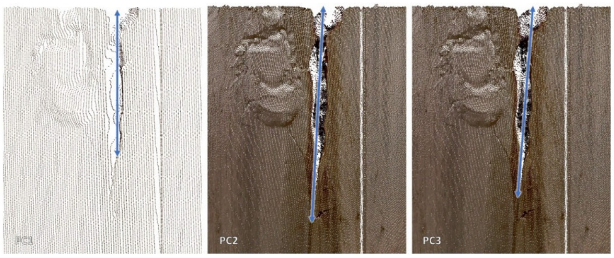

Figure 8. Measurements of roughness in discontinuities D1 (left) and D8 (right) using point cloud PC3

Table 4. Results of spacing between discontinuities

Interval	Façade	Spacing (m)		
		PC1	PC2	PC3
D1–D2	SW	1.06	1.05	1.06
D3–D4	NW	0.23	0.24	0.26
D4–D5		5.24	5.26	5.24
D5–D6		0.58	0.59	0.55
D6–D7		4.87	4.87	4.85
D7–D8		1.20	1.23	1.19
D8–D9		3.12	3.14	3.12
D9–D10		6.05	6.05	6.02
D10–D11		10.49	10.55	10.56
D13–D14	NE	1.17	1.19	1.17
D14–D15		2.38	2.39	2.37
D15–D16		12.76	12.69	12.79

Spacing does not vary significantly between point clouds, as the measurements are made perpendicularly to the general direction of consecutive discontinuities, which is possible even in a sparse point cloud.

Deepness was measured based on the façade planes and the corresponding maximum distance within the identified hollow vein (D9). Alternatively, as in the measurement of aperture, it could be expressed by measuring the distances to the façade at predefined heights, or through the modelling of the discontinuity shape by an interpolated mesh. This last option requires additional care during data preparation and capture, as the accuracy of the registered values is strongly dependent on the scan positions and point cloud densities (Figure 9).

Figure 9. Estimation of deepness for hollow vein D9

3.6. Discussion on results

The data clearly show that not all discontinuity parameters need the same point cloud density. Spacing and dip/dip direction are highly consistent across PC1, PC2, and PC3 (often differing by only 1°–2°), while aperture and persistence show greater sensitivity to resolution and scan position. Across all the point clouds in the case study, spacing values are remarkably stable, with differences typically under 0.05 m. Dip direction and dip angle are reliably captured at both resolutions of the experiment. The tabulated values show very small inter-scan differences, suggesting that even lower-resolution scans (6.1 mm at 10 m) are adequate for orientation characterization. As for aperture, its variation along a discontinuity is captured by TLS with different configurations, but the three-point measurements of this parameter (at 1/3, 1/2, 2/3 of extension) reveal that many discontinuities have highly variable values. Persistence is the parameter most sensitive to scan configuration. The large differences observed in two of the identified discontinuities across point clouds suggest that identifying their endpoints is the most variable step, highlighting the dependence on the device configuration, namely the resolution.

The merged point cloud (PC3) offers marginal additional benefit for most parameters. Since PC3 combines both scan positions, one might expect systematically better results, but the data don’t show this consistently. For orientation and spacing, the first two configurations alone would suffice, which suggests that multi-scan surveys are only strictly necessary for aperture and deepness characterization.

4. Conclusions

Using TLS equipment in the acquisition of point clouds, where very detailed geometric representations can be obtained, opens the opportunity to use the digitized model of a quarry as a basis for detecting discontinuities and measuring some of their characterizing geometries. The definition of a network of scan positions is decisive for the correct extraction of some parameters and complete coverage of the intended façades. The distances between equipment and façades, which affect the point cloud parameters, should be considered in the planning stage. Also, the capture of images and the assignment of a radiometric level to each scanned point is an advantage, as it facilitates the discrimination between joints and veins, and allows a better characterization. One of the most important advantages of the digitization of a quarry using a laser scanner acquisition technique is the availability of the model for revisiting, validation, data sharing with other specialties, and as a basis for monitoring.

The purpose of this work was to analyze the possibility of using a laser scanner survey to map and characterize discontinuities in limestone rock masses in a quarry environment. The obtained results indicate that the use of laser scanning technology enables the visualization and identification of discontinuities in limestone rock masses. After conducting measurements in various configurations of the laser scanner and subsequent processing of the results, it can be concluded that, in the obtained final data, the differences between scans and settings have a different impact on the various extracted characterizing values. The adequacy of point clouds obtained by TLS in the geometrical characterization of discontinuities is highly dependent on the parametrization of the equipment and the geometry of scan positions. Some characteristics (aperture, roughness) require more detailed point clouds, due to the involved dimensions and the need to use the shape of the discontinuity. In addition, the evaluation of deepness requires establishing a network of scan positions to guarantee that an adequate set of points, able to characterize the shape inside the hollow veins, is obtained. On the other hand, the characterization of persistence, spacing, dip angle, and dip direction is less demanding in terms of point cloud density. The measurement of aperture can be performed along the discontinuity alignment at various points, enabling a better characterization, even when the physical accessibility of the façade is compromised, or the height of the façade is a barrier.

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Author contributions

Maciej, C., APF and ABG conceived the study and were responsible for the design and development of the data analysis. Maciej, C., Magdalena, C., APF, ABG and RM were responsible for data collection and analysis. Maciej, C., RM, PS, and MCS were responsible for data interpretation. Maciej, C., APF, and ABG wrote the first draft of the article.

Disclosure statement

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