Roughness measure of a large in situ discontinuity surface by non-contact survey

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ABSTRACT: Roughness of rock joint surface plays a key role in the stability conditions of rock slopes and it is commonly assessed on small portions of the outcropping surface or laboratory samples. However, roughness is naturally dependent on the considered scale, the analyzed surface sector (surface heterogeneity), and the direction of measurement (surface anisotropy). Therefore, the scale effect, heterogeneity and anisotropy should be quantitatively assessed to understand their role in shear resistance variations. This paper describes the surveys carried out on an extensive natural discontinuity in a slope along the Elva Valley Road (Northwestern Italy) subject to frequent and intense instability phenomena. A digital surface model (DSM) of the entire surface was obtained through UAV (Unmanned Aerial Vehicle) photogrammetric technique and the resulting point cloud was analyzed in order to measure the spatial variability of the surface roughness considering the different directions and the surveying interval.

Keywords: Roughness, scale effect, Morphology, Non-contact survey.

1 INTRODUCTION

A proper characterization of rock discontinuities is essential in slope stability conditions analysis. Roughness represents one of the most important geometric features strongly influencing the shear resistance of the joints. The roughness of a rock joint surface is commonly assessed on small portions of the outcropping surface or laboratory samples. However, roughness is naturally dependent on the considered scale, and all the roughness descriptors are scale-dependent, too. Therefore, the scale effect is worthed to be quantitatively assessed to understand its role in shear resistance variations (Ferrero et al., 2019).

In the literature, several methods have been proposed to measure and characterize the roughness of discontinuities: manual and subjective methods that require physical contact with the surface and highly advanced remote and automatic methods. These latter methods use improved technologies to obtain morphological information remotely, through processing point clouds and 3D models, useful for characterizing the rock mass. Recent studies demonstrate that it is possible to measure the roughness of rock discontinuities using UAV point clouds which allow information to be obtained in challenging environments characterized by high and steep rock walls (Salvini et al., 2020).

This paper describes roughness investigations conducted on an extensive surface of discontinuity located along the Elva Valley Road, on the orographic left of the Maira Valley (Piedmont, Northern Italy). This road stretches for 9 km and is affected by numerous instability phenomena, including a large planar sliding (occurred in 2015), for which the road was closed to traffic (Migliazza et al., 2021). Specifically, Figure 1a shows a photo of the section under study, which presents an evident orientation of the rock strata in the slope direction (inclination between 45 and 50°), with a height of about 70 m and slabs about 1 m thick. The rock face was disturbed by the construction of the road and its widening. This site manifested planar sliding phenomena that progressively mobilized slabs or portions of slabs released at the foot by the reprofiling of the slope.

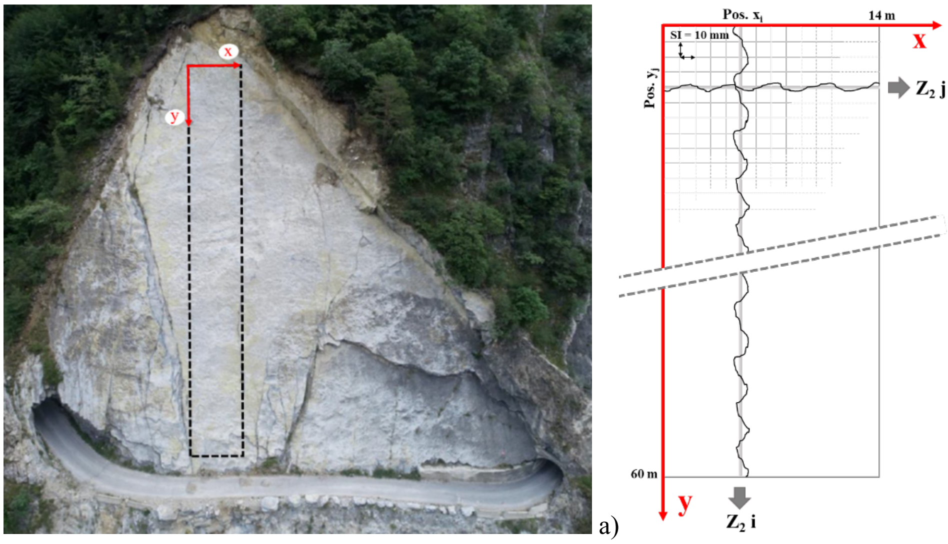

Figure 1. a) The current state of the surface under study, Elva Valley Road; b) Grid scheme showing profile directions x (position i) and y (position j).

The slope is located in an area characterized by dolomitic limestones, significantly deformed, with both folds and faults. The bedrock is characterized mainly by three discontinuity sets: a very persistent bedding plane and two other conjugate joint sets (mutually perpendicular as well as perpendicular to the bedding plane) characterized by a persistence defined by the bedding planes spacing. The orientation of the planes varies along the Valley due to the presence of folds and faults, and for this reason, different kinematic conditions are identified along the road. The surveyed area is a bedding plane surface along which a large planar sliding occurred in 2015.

The surface was subjected to a photogrammetric survey through which the point cloud and the DSM of the surface could be obtained. Through analytical procedures, the DSM was used to evaluate the geometric descriptor Z_2 (Myers, 1962) In particular, two aspects were analyzed in this study: the scale of observation and the anisotropy of the surface, considering different Sampling Intervals (SI).

2 METHODOLOGY

2.1 Survey Methodology

The dense point cloud and associated DSM of the slope under study were obtained through UAV photogrammetric technique supported by a GNSS (Global Navigation Satellite System) topographic survey (Pontoglio et al., 2020).

During UAV surveys, about 185 digital images (both nadiral and oblique) were taken in 4 flights by using a commercial drone (DJI Phantom 4, with a FC6310 camera, 20 MP CMOS Complementary Metal Oxyde Semiconductor sensor, focal length of 8.8 mm).

To georeference the processed digital model, a topographic network was designed. 30 points were measured using GNSS or total station techniques, ensuring high accuracy and precision (σ_{max}= 3 mm in the vertical or horizontal direction).AMS software (Agisoft Metashape Professional, vrs. 1.7.4) was used to process the photogrammetric data. A high-density point cloud was generated (approximately 1 point per cm^2 for about 199 million points) using 1/5th of the points of the originated dense point clouds to generate the high-resolution mesh.

2.2 Data analysis

The DSM representing the investigated surface consists of a TIN (Triangular Irregular Network) of 3D points evenly scattered, with a density of about 1 pts/cm^2. The surface is almost planar, therefore a proper local reference system was set (Figure 1a and b): the xy plane corresponds to the 3D point cloud best-fitting plane, where y-axis follows the maximum slope (shear direction) and x-axis is consequently orientated; z-axis is positive towards the outside, and it indicates the asperities height variation. The original x and y coordinates of the points cloud were converted into a regular grid having a constant spacing of 10 mm in both directions. The z values are obtained in correspondence to each grid node by a Kriging interpolation of the original ones. In this way, asperity profiles along both x and y directions were obtained and analyzed in terms of their roughness measure.

Among the statistical descriptors based on the geometry of rock joints profiles that are available in the literature, we considered the root mean square of the first derivative, called Z_2 (Myers, 1962; Tse and Cruden, 1979; Yu and Vayssade, 1991; Yang et al., 2001), defined, for a profile along the x direction, as:

$$Z_2 = \left(\frac{1}{L}\sum_{i=1}^{N-1}\frac{(z_{i+1}-z_i)^2}{x_{i+1}-x_i}\right)^{1/2} \tag{2}$$

where L is the projected length of the profile, z is the asperity height and x_i is the abscissa of the i-th sampling point (y_i in the other direction).

About 6000 profiles along the x direction (x-profiles) and 1400 along the y one (y-profiles) were analyzed by means of a self-developed Matlab script varying the SI along the profile, and calculating the corresponding values of Z_2. The first aspect on which we have focused our attention in this study is the scale of observation, to understand the contribution of the waviness (large-scale undulation that can cause dilation during shear displacements) and the roughness (small-scale roughness that tends to be damaged during shear displacements) (ISRM, 1978).

The second investigated aspect is the geometrical anisotropy, namely, the influence of measurement direction on roughness assessment (Tatone and Grasselli, 2013; Carriero et al., 2023).

3 RESULTS

The original grid profiles, whose SI is equal to 10 mm in both directions, were taken as reference: the corresponding Z_2 values were calculated for each x- and y-profile, and their trends along the y and x-axis, respectively, were analyzed with the aim to identify homogeneous portions and possible anomalies to be further investigated.

Figure 2 shows the variability along the y direction (upper diagram) and x direction (lower one) of the Z_2 values obtained for the y- and x- profiles, respectively. It can be noticed that Z_2 values are, in general, smaller along the maximum slope direction (y) with respect to those along the perpendicular one (x): as expected, the previously occurred sliding phenomena had reduced the surface asperities along the motion direction (y direction). Moreover, it is reasonable to consider as homogeneous the area extending from 12 to 47 m along y direction and from 4 to 12 m along x direction.

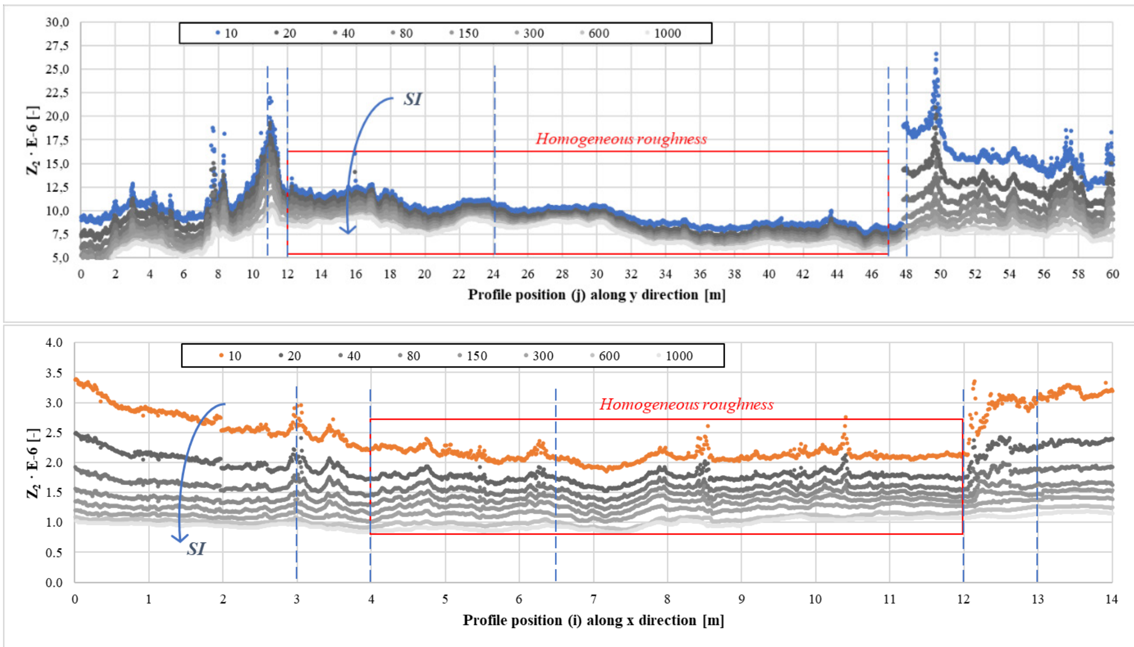

Figure 2. Trend of Z_2 by varying SI along up) x direction; down) y direction. The abscissa represents the position of the profile along the corresponding perpendicular axis (respectively, position j and i).

3.1 Measurements scale effect

The influence of the SI was investigated by analyzing x and y-profiles generated by considering an increasing point-step, namely one point every two (SI = 20 mm), one every three (SI = 30 mm), and so on to a maximum SI of 1m. The results obtained for the most significant SIs are shown in Figure 2. As expected, an increasing SI has a smoothing effect on Z_2. This effect is more evident outside the homogeneous area and particularly in areas where Z_2 values are higher. In particular, it is evident that when a certain value of SI is exceeded, the small-scale roughness information is lost, and only waviness is captured.

Figure 3 shows the value of Z_2 calculated for five profiles (dashed lines in Figure 2) in both directions and for different SI values used for their sampling. Three profiles inside the homogenous area and two outside, at the limits of the homogenous area, were considered. It is possible to notice that in all the cases analyzed, the measure of roughness (Z_2) is strictly connected with the sampling interval chosen, and it decreases as SI increases.

To define the value of SI for which the variation of Z_2 is negligible, the slope of the curves was computed, defining a threshold (Figure 4) as:

$$\frac{\Delta Z_2}{\Delta SI} < 0.003 \cdot 10^{-6} \;\; [mm^{-1}] \tag{3}$$

A value was set for which the slope of each section can be considered zero, which corresponds to an SI limit of 100 mm for all profiles. For SI > 100 mm the roughness information is lost and the Z_2 measurement is relative to waviness only.

3.2 Anisotropy

Regarding the anisotropy, the results obtained along x and y considering SI equal to 10 mm were compared. The roughness variability, measured along the discontinuity surface in both directions, was analyzed considering the Z_2 frequency distribution obtained in the 6000 profiles along x direction and the 1400 profiles along y one (Figure 5). It is evident that the surface exhibits both heterogeneous and anisotropic features in the two directions, showing a lower roughness along the slip direction (y direction).

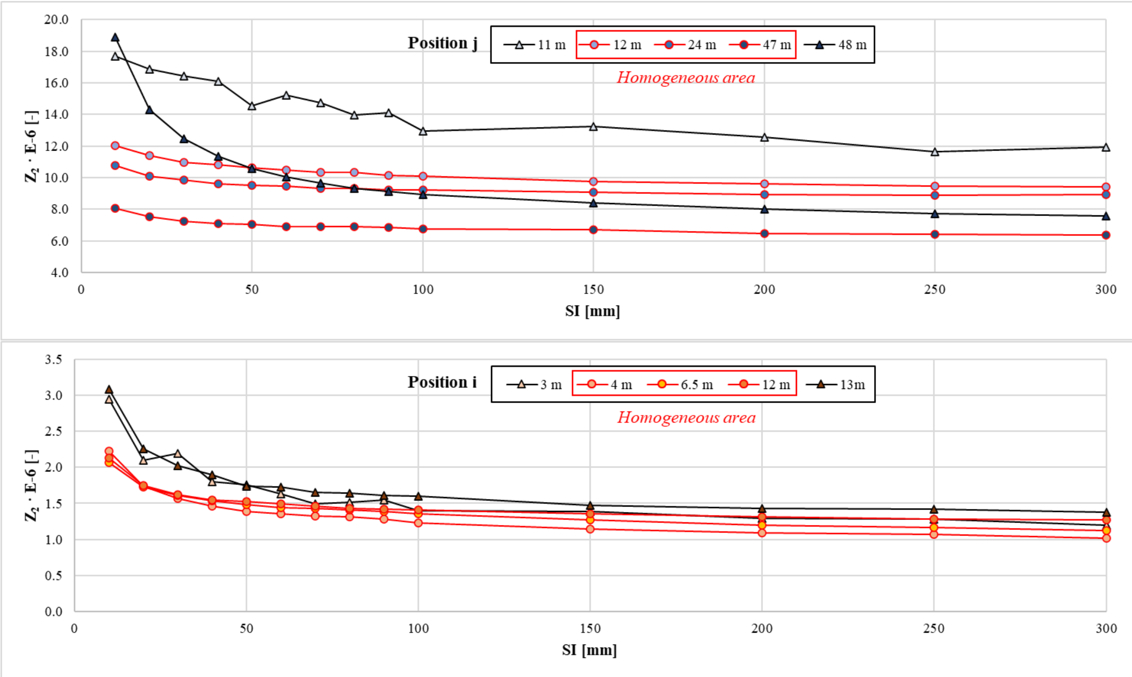

Figure 3. Trend of Z_2 in 5 significant profiles: 3 within the homogeneous area (red lines) and 2 outside (black lines), by varying SI, along up) x direction; down) y direction.

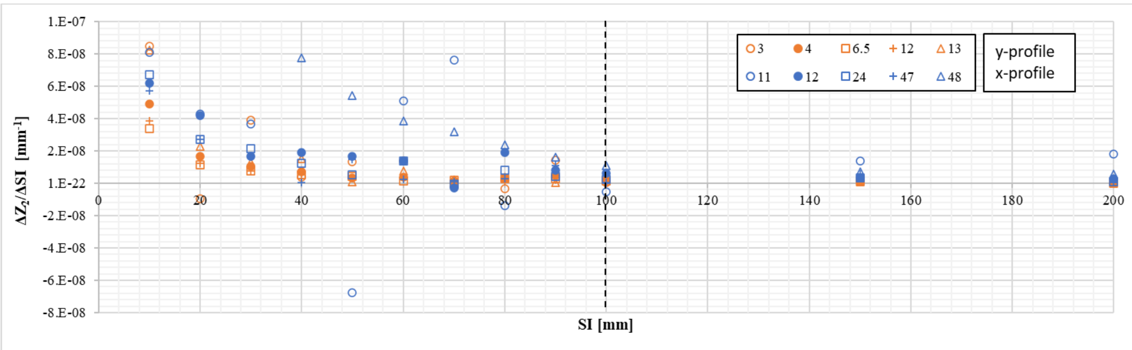

Figure 4. Slope of Z_2 curves to define the SI threshold of 100 mm.

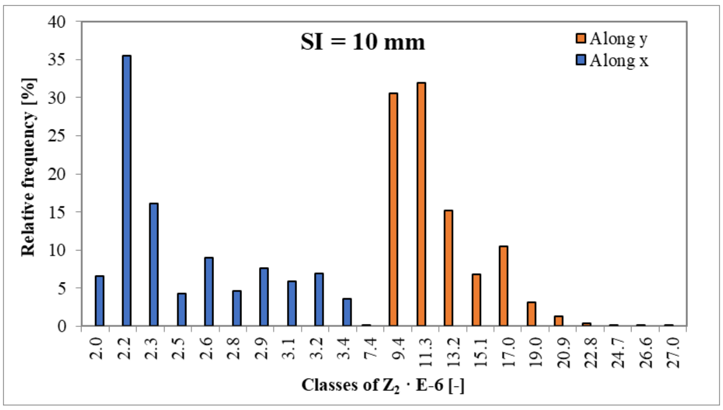

Figure 5. Frequency distribution for profiles along x and y, considering 20 classes of Z_2, SI equal to 10 mm.

4 CONCLUSIONS

This paper describes the surveys carried out on an extensive natural discontinuity in a slope along the Elva Valley Road subject to large planar sliding. A DSM of the entire surface was obtained through UAV photogrammetric technique and the resulting point cloud was analyzed to evaluate the geometric descriptor Z_2. In particular, two aspects were analyzed in this study: the scale of observation and the anisotropy of the surface, considering different SIs.

From the analysis of the scale effect, it can be seen that in all the cases analyzed, the roughness (Z_2) measurement is closely related to the chosen SI. In fact, for SI greater than 100 mm, the small-scale roughness information is lost and the Z_2 measurement is related to waviness only.

In addition, it is evident that the surface exhibits both heterogeneous and anisotropic features in the two directions, showing lower roughness along the slip direction (y direction).

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