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Terrestrial Laser Scanning survey of the Sugano cliff (Orvieto, Italy) for slope stability analyses

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ABSTRACT

The Terrestrial Laser Scanner (TLS) survey of the Sugano (TR, Italy) cliff has been performed with the aim of assessing by a remote position the main rock mass jointing features (such as dip/dip direction, spacing, opening, persistency etc). Geostructural analysis has been performed on the high resolution 3D point clouds collected in the frame of a two days survey by combining six survey positions. The results from the remote investigation of the cliff allowed to identify the limit equilibrium conditions for all the studied cases and provide geometrical information (volume, surface etc.) of the blocks more susceptible to instability.

Specifically, the kinematic of rock mass blocks was proved compatible with toppling phenomena tests under two independent triggering conditions: (a) hydrostatic water pressure within the joints and (b) seismic action. Safety factor (SF) values were attributed to these blocks in every studied conditions.

KEY WORDS: Geostructural Analysis, Rock topples, Safety Factor, Terrestrial Laser Scanner.

INTRODUCTION

Rock topples are slope movements affecting natural and artificial slopes characterized by the detachment of blocks or rock fragments, ranging in size from few dm^3 to several hundred m^3 (Cruden & Varnes, 1996). The detachment of blocks form a rocky slope is mainly influenced by three factors: i) the structural conditions of rock mass, i.e. the joint set feature (e.g. orientation, persistency, roughness); ii) the mechanical properties (shear strength of discontinuities, the tensile strength of any rock bridges) and iii) external stresses like the presence of pressured water in the discontinuities, the seismic actions due to earthquakes, roots growth etc.

Rock topples are very common in mountain and hilly regions. Despite the volumes of involved material can also be quite small, these events are characterized by a high temporal frequency of occurrence and, therefore, a frequent interaction with mankind and with human activities (Hungr et al., 2013).

The combination of conventional contact investigation techniques able to provide detailed point based information with widespread remote sensing solutions such as Terrestrial Laser Scanning is getting and increasing importance and interest in the scientific community (Sturzenegger & Stead, 2009; Jaboyedoff, 2010; Martino & Mazzanti, 2014).

This paper describes the results of a detailed investigation carried out on a cliff frequently affected by instability processes located in Sugano (Orvieto, Italy). The 3D high-resolution point clouds collected by Terrestrial Laser Scanner (TLS) surveys (Lato et al., 2009; Abellàn et al., 2010) were the starting point of the analysis. Specifically, the following investigation procedure was adopted:

i) analysis of joint features (i.e identification and parameterization of the main joint sets, estimation of standard joint index Jv (ISRM, 1978), analysis of persistency and opening of joints) through the study of point clouds and the execution of a geomechanical survey on site;
ii) kinematic compatibility analysis performed using the Markland (1972) tests for rock topples;
iii) sensibility analysis for rock topples in relation to different possible triggering factors (simulation of scenarios);
iv) detection and geometric characterization of blocks potentially susceptible to instability processes.

GEOLOGICAL SETTING

Sugano (Fig. 1) is a small hamlet of Orvieto Municipality and it is located to the west of the Orvieto City in the province of Terni (Umbria, Central Italy), about 100 km north of Rome, standing on the northern edge of a broad Quaternary volcanic plateau (Alfina plateau) outcropping in almost the whole northern Latium (Cencetti et al., 2005). The current geological configuration of Sugano is similar to the Orvieto one: it is the result of neotectonic and volcanic events taking place in the Quaternary period. Its eruptive center (Vulsini Volcanic Complex) corresponded to the present-day Bolsena Lake (Nappi et al., 2004). The substratum of the volcanic Alfina plateau is made up of Pliocene marine clays: after the total retreat of sea from the area, an extensional tectonic phase started during Lower Pleistocene. This resulted in a normal fault striking approximately NW-SE, the raised block of which

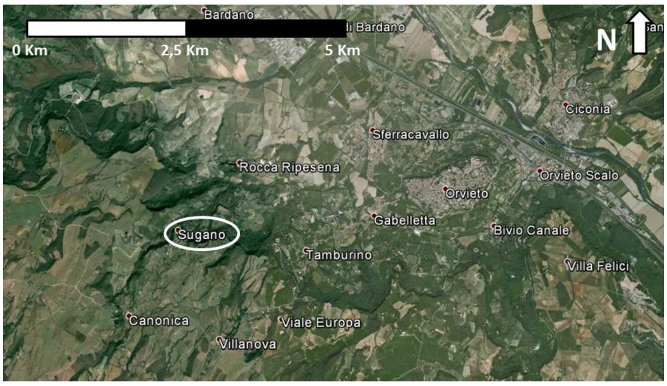

Fig. 1 – Location of the Sugano cliff on satellite optical image.

acted as a "wall" against which the volcanic magma flows and pyroclastic deposits of the "Apparato Vulsino" accumulated (Cencetti et al., 2005). The erosion of the Paglia River was one of the most important responsible of the current morphological configuration of some cliffs in the area, such as Orvieto, Sugano and others. Because of their erodibility, the Plio-Pleistocene marine clays represent a sinking substratum, causing lateral spreading phenomena with consequent rock topples in the upper volcanic formations, affecting the edges of the cliffs since historical times (Bozzano et al. 2008).

TERRESTRIAL LASER SCANNER

Terrestrial Laser Scanner (TLS) surveys were performed by a Riegl VZ1000 sensor from six different scan positions in order to reduce the shadow zones (Fig. 2). The system was equipped with a GPS antenna, an inclinometer sensor and a digital compass (for the georeferencing of the achieved data) and a high resolution digital camera, thus allowing the acquisition of real color 3D models. A topographic survey was also performed by a Leica TCRM1202 total station (TS) in

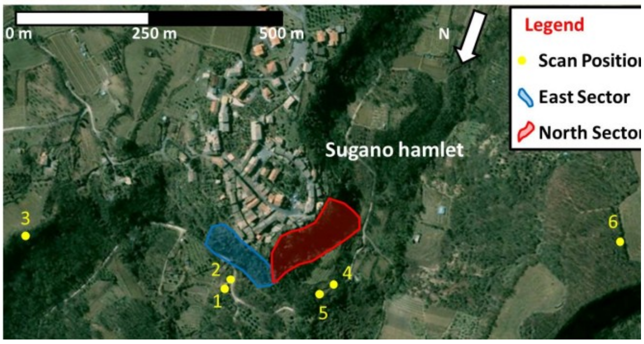

Fig. 2 – Identification of scan positions on satellite image.

order to geocode all the collected point clouds in the same geographic reference system during the post-processing data management.

The Sugano cliff is characterized by two slopes with orientation, respectively, of about 10° and 100° respectively. On this basis, the sectors are indicated as North and East sector and are separately analysed because the alignment of point clouds was performed on the basis of control points visible from the different scan positions. The software used for registration, alignment and processing of acquired point clouds was Riscan Pro (Riegl, 2008). By post-processing data management, all point clouds collected from different scan positions were aligned in order to get a single extended point cloud of the whole investigated scenario. In areas covered by vegetation, the point cloud was treated by manual and automatic filtering in order to delete all elements not corresponding to outcropping rocks. When laser hits an obstacle, such as vegetation, part of the signal is reflected while another part overtakes the obstacle by reaching the study object (in this case the cliff). Basing on the analysis of multiple returns of the laser beam ("Echos"), it is so possible to acquire information also in areas partially covered by vegetation. In particular, there are four different types of Echos: Single targets, First targets, Other targets and Last targets. First targets and Other targets are considered like areas covered by vegetation because represent, respectively, the first and multiple returns of the signal in presence of obstacles like vegetation. On the contrary, Single targets and Last targets are considered like signals reflected by the outcropping rock.

In the present study, the points of acquired clouds were organized by using an octree, one of the filtering procedure of Riscan Pro software. This method consists in an additional removal of the vegetation, but, respect to the previous procedure, the "obstacles" are manually deleted. This process is performed on a Polydata, object upon which it is possible to modify and perform other procedures by keeping the original characteristics of the point clouds.

After the filtering procedure, a mesh was created by a 2D-Delaunay triangulation algorithm (Shewchuk, 1996). The achieved result is a 3D solid model with cell resolution ranging from 0,003 m^2 to 0,6 m^2. Additional automatic and semi-automatic filters were also applied in order to remove outliers artefacts and to get an homogeneous model.

GEOSTRUCTURAL ANALYSIS

Geostructural characterization of the Sugano cliff was based on manual and automatic analysis performed on the achieved TLS point cloud by Split-FX - Free Demo Version software (http://www.spliteng.com/split278fx/; Strouth and Eberhardt, 2006). The aim of the analysis was to achieve information about the rock mass joint pattern and its features for the following prone to instability investigations. After the realization of a mesh through irregular triangulation of the point cloud, the patches (areas defined by mesh cells laying on the same plane) was automatically identified through parameters defined by the operator, that is the Minimum patch size and Maximum neighbor angle (defining the size of accepted patches and the tolerance used to form them).

Patches were also manually identified and drowned by expert operators through the navigation of the 3D mesh model. Patches identified by both approaches were analyzed in order to identify the main joint sets of the rock masses, thus providing their spatial orientation. Poles of identified patches joints were plotted on the Schmidt equi-areal stereographic projection (lower hemisphere). Table 1 shows the joint set data obtained for all the investigated outcrops.

	Joint set	*Strike* of joint set	*Dip Direction*	*Dip*	*Strike* of slope
EL outcrop	EL1	N-S	270	85	N40W
	EL2	N80W	190	85	
EU outcrop	EU1	N33E	303	80	N4W – N33W
	EU2	N70W	200	80	
N outcrop	N1	N35W	229	88	N80E
	N2	N70E	340	75	

Tab. 1 – Data of joint sets for all over the outcrops: EL and EU indicate the outcrops analysed for East sector, respectively lower and upper outcrop, while N indicate the outcrop analysed for North sector of the Sugano cliff.

Two main joint sets were identified for all the outcrops analyzed. The joint sets of the two outcrops of the East sector are almost concordant and characterized by high Dip angles, isolating blocks of columnar shape. Their Dip Direction values are rather different than those in the North sector, where one of the two systems are sub-parallel to the direction of the slope and represent the main surfaces of detachment of blocks.

All joint sets, identified in the investigated sectors of the Sugano cliff, present high values of persistence (average values ranging between 70% and 80%), expressed as percentage length of the joint respect to the whole outcrop. Average values of Jv ranging between about 0,7 joints/m^3 and 2,4 joints/m^3 were obtained respectively for EU and N outcrops and for the EL sector outcrop. Apart from tightened joints or characterized by opening values less than 1 cm, the analysis of the opening highlighted opening values ranging approximately between 3 and 7 cm. An exception is represented by a released area of the rock mass (located at the intersection of the East and North sectors of the cliff), with end-member opening values ranging between 8 and 75 cm. These data show that outcrops are characterized by the presence of large blocks, that present a prismatic shape on the basis of the joint sets identified.

On the basis of the geostructural analysis, some potentially unstable rock blocks were identified on the whole investigated area of the Sugano cliff and their volume was calculated by the Riscan Pro software, ranging from about 0,2 m^3 and 90 m^3, except for a localized sector where a 210 m^3 hazardous block was identified.

PARAMETRIC STABILITY ANALYSIS

The stability conditions of the Sugano cliff were analysed on the basis of jointing conditions of the rock mass. Two sub-vertical joint sets, identified by geomechanic analysis, shall release the prismatic blocks and, therefore, rock topples mechanism was considered for the slope stability analysis. Firstly, a preliminary kinematic compatibility analysis was performed by Markland (1972) test. The second phase of the analysis consisted in the study of different static and pseudo-static scenarios (seismic action and presence of water pressure in the joints). For all the supposed scenarios it was attributed a SF (Safety Factor), computed as the ratio between the stabilizing and the destabilizing force-momentums. The variations of SF were plotted as a function of water height H_w and pseudostatic coefficient k_x. Furthermore, the relation between water height H_w and pseudostatic coefficient k_x was plotted by representing the stability chart. The East sector of the cliff reaches limit equilibrium conditions to rock topples when the values of water height in the fractures range between 1,6 and 2,5 m or when the values of pseudo-static coefficient range between 0,03 and 0,08. The North sector of the cliff reaches limit equilibrium conditions to rock topples when the values of water height in the fractures range between 7 and 7,4 m or when the values of pseudo-static coefficient overcome 0,17.

CONCLUSIONS

The present study demonstrates the reliability and importance of remote sensing techniques for the characterization of rock masses prone to instability and prove their advantages respect to other conventional techniques, especially in the investigation of inaccessible sectors of the slopes. A detailed geostructural analysis of the Sugano (TR, Italy) cliff was performed on the 3D high resolution point cloud collected by Terrestrial Laser Scanner (TLS) remote surveys. The joint sets, identified in the two East sector outcrops (EL and EU), are concordant and characterized by high Dip angles that isolate blocks of columnar shape. Strike and Dip angles of joint sets identified in the North sector outcrop (N) are rather different in terms of Dip Direction respect to the East sector, although also characterized by high Dip angles. The kinematic compatibility analyses performed by the Markland (1972) test on the typical rock mass blocks (defined for each sector basing on the geostructural results) allowed to attribute to rock toppling the major role for the morphological evolution of the Sugano cliff. Limit equilibrium analysis allowed to assess an overall stability condition of the slope without any triggering factors; on the contrary, instability conditions can be achieved, in most of the outcropping rock mass, for realistic triggering scenarios (seismic action and hydrostatic water pressure).

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