Rend. Online Soc. Geol. It., Vol. 39 (2016), pp. 113-116, 5 fig., 1 tab. (doi: 10.3301/ROL.2016.60)

Remote sensing investigation techniques for the analysis of rocky slope stability in remote areas: a test from the Sierra Madre Occidental, Mexico

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Document type: Short note

Manuscript history: received 29 October 2015; accepted 07 January 2016; editorial responsibility and handling by Sebastiano Trevisani.

ABSTRACT

Direct field survey to assess slope stability in steep and remote rocky cliffs is time demanding and highly consuming in term of human and economic resources. However, evolving technologies allow remotely sensed data integrated with GIS to theoretically provide equivalent information. Here we present a case study comparison of these methods applied to the Eastern valley-side of the Chinipas River, Sierra Madre Occidental, Mexico.

Results show that remote sensing procedures provides the same discontinuity sets and equivalent attitude information with respect to the data acquired during field survey.

KEY WORDS: Slope stability, Discontinuities attitude, Structure-from-motion, GIS, Mexico.

INTRODUCTION

For the analyses of rocky slope stability, information regarding the spatial geometries of the fractures are of fundamental importance (ISRM, 2007). In particular, data regarding discontinuities attitude are essential for assessing slope failures (Hoek & Bray, 1981) possible from a kinematic point of view. Generally, orientation or attitude can be expressed by strike and dip values collected during structural surveys, which in steep and remote rocky cliffs are time demanding and highly consuming in term of human and economic resources. However, evolving technologies allow remotely sensed data integrated with GIS theoretically provide equivalent information (Deb et al., 2008; Grenon & Laflamme, 2011; Marchesini et al., 2011; Westoby et al., 2012). Here we present a case study showing a comparison of direct field survey and remote sensing procedure to evaluate discontinuities attitude.

GEOLOGICAL – GEOMORPHOLOGICAL SETTING

The rocky cliff investigated is located in the North Mexico in the western side of the Sierra Madre Occidental (SMO), known also as Sierra Tarahumara, along the Eastern valley-side of the Chinipas River between the Chihuahua State and the Gulf of California (Fig. 1a).

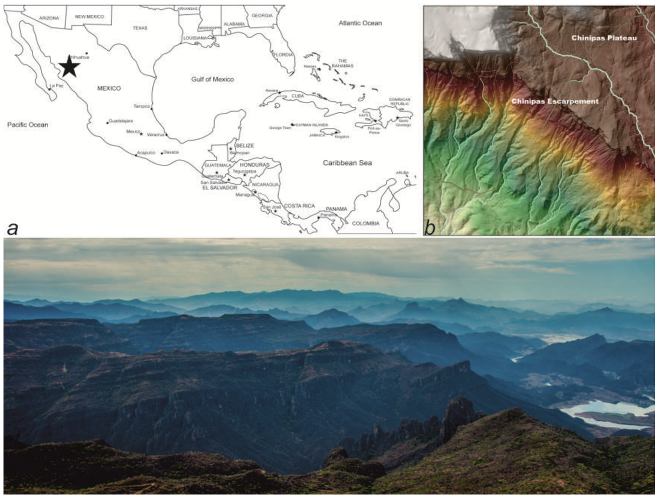

Fig. 1 – Location of the study area in Central America (a) and elevation map of rocky cliff in Chinipas Region (maximum and minimum elevation 1500 m and 300 m asl, respectively) (b); panoramic view of the Sierra Madre Occidental (c).

Abrupt changes in elevation, alternating between narrow, faulted mountain chains and flat arid valleys, characterize the area (Fig. 1b). The sector investigated is characterized by volcanic plateau hanging at elevation from about 1050 up to 1.500 m a.s.l., interrupted in its south-western edge by a series of rocky cliffs (escarpments) with heights from 10 m up to 150-200 m (Fig. 1c). The rocks outcropping in the Chinipas slope consist of thick sequences of rhyolitic tuffs, ignimbrites and basaltic lava bodies of the Miocene age overlying a polimitic conglomerates and arenites of Oligocene age with a thick of many hundreds meters (Ferrari et al., 2007).

In the rocky cliff investigated there are at least two basaltic lava bodies, about 50 m thick, separated by an ignimbrites level of 15/20 m of thickness. Rubbly levels at the top and base of the lava bodies ('a'a lava flow) suggest an emplacement of the pyroclastic material in an already weathered surface. The lava bodies dips gently trough NE with a dip of few degrees and are affected by several systems of fractures and characteristic columnar joints.

The main tectonic features consist of fractures and joints affecting the rock mass, while one normal fault SW dipping, with an offset on few hundred meters is present at the base of the slope. This fault, which runs parallel to the Chinipas river valley, belongs to the extensional system striking NW-SE affecting the western side of the Sierra Madre Occidental.

The main geomorphological processes at the Chinipas slope are those due to gravity and superficial running waters.. A major polygenic scarp characterizes the cliff area. The NW-SE striking escarpment is due to the differential action on fractured rocks of gravitational phenomena combined with physical weathering. At the foot of the scarp, a wide debris composed by decimetric breccias and metric to pluri-metric boulders were interpreted as the product of coalescent and repeated rock falls. In the rock mass, groundwater circulation is connected with direct seepage into the fracture zones, while there is no interaction with the streams and runoff water.

METHODS AND RESULTS

Aim of this study is the comparison between traditional field survey approach and remote sensing techniques to identify rocky mass discontinuities and related slope instability.

FIELD SURVEY APPROACH

The survey was executed during the dry season in June 2014. The geomorphological field survey was aimed at identifying the geomorphic evidence of slope instability and active tectonics, tracing deformations due to present active landsliding and recent tectonic activity. The structural and geomechanical survey of basaltic lava, ignimbrites and tuffs that crop out on the slope allows identifying and describe the discontinuities of the rocky cliff (Fig. 2). In Chinipas area, several of discontinuities affecting the rock mass have a thermal origin, although other types (i.e. gravitational, tectonic and diagenetic) can be observed extensively. Thermal discontinuities due to cooling and retraction processes are: vertical, columnar, polygonal, radial, sub-horizontal and spherical jointing observable on the SE part of the escarpment. In the investigated area, the rock mass is affected by a system of sub-vertical discordant dikes, intruded along pre-existing faults and fracture systems, generally vertical or sub vertical, developed along the NW-SE direction, with a thickness variable from 1 to 3 m. Discontinuities formed by gravitational processes (i.e.tension cracks, collapse fractures associated to rock falls), can be detected in correspondence of the slope face. Major discontinuity plans are developed along the contact of the surfaces between lava formations with clinker layers and rubbly levels. Geomechanical survey stations, representative of the geological-structural condition of the whole cliff, were carried out on different positions of the slope using traditional techniques, such as scanline method. The characterization was carried out according to the ISRM (2007) standard and the data collected includes information on rock discontinuities, lithology, hydrology and rock compressive strength measured by a Schmidt hammer (Priest, 1993).

REMOTE SENSING INVESTIGATION

The remote sensing dataset was derived from a three-dimensional virtual reconstruction of the volcanic bedrock exposure along the Chinipas escarpment. The area covers a

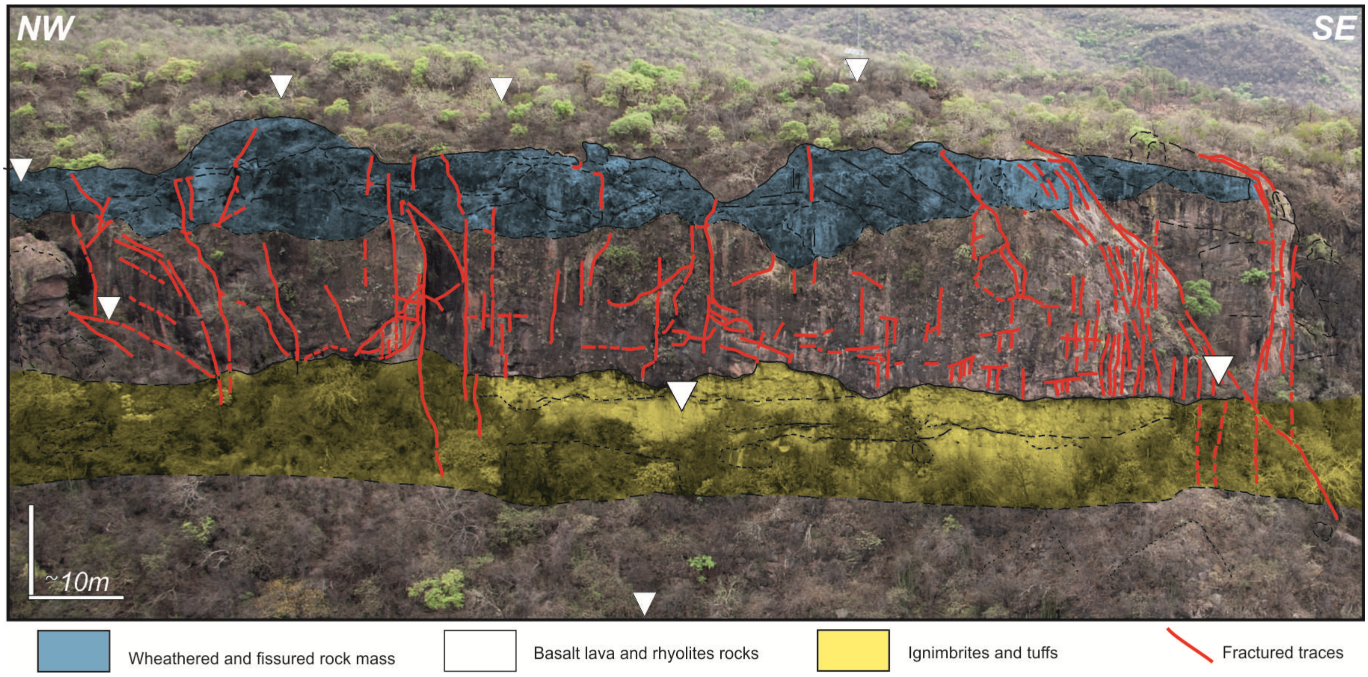

Fig. 2 –Rock types and main discontinuities traces of the rocky cliff resulting from field and remote surveys. The triangles are the ground control points (GCP).

surface of about 0.5 km^2 over a distance of about 1 km. A workflow was developed starting with oblique digital photographs that were processed using the Structure from Motion (SfM) algorithm for obtaining initial points cloud. There are several software packages where this algorithm is implemented for processing images of the same object taken from different point of view (Arbués et al., 2012; Favalli et. al., 2012). These software which can be freeware, like Photosynth (Microsoft ®) or SFMtoolkit3 (Astre, 2010), or commercial, like Agisoft Photoscan (Agisoft ®) or Pix4D (Computer Vision Lab ®), permit to obtain a 3D point clouds.

A sequence of about 60 georeferenced oblique digital photographs was acquired from a helicopter platform. The camera used was a hand-held digital Single-Lens Reflex (SLR) Nikon D700 equipped with a calibrated Nikon 35 mm f/1.4 lens. The focal length of the lens was fixed to infinity to ensure that all photos were taken with the same focal length. The photos were taken with a resolution equal to 12.1 megapixels (4.256 x 2.832) in RAW format. Each photo was georeferenced through a GPS unit (GNSS) located above the camera body. The photos geo-location was subsequently checked using Ground Controls Points (GCPs) and overlapping them on an available Digital Elevation Model (DEM) acquired from LIDAR. The average accuracy of the GCPs locations by means of GPS was about 1 m.

Over a set of images of the same object, the SfM algorithm detects suites of common points in each image that have the same colours gradient (Lowe, 1999). Considering the camera and lens parameters distortions, the 3D coordinate of the detected points were extracted and a points cloud was generated (Westoby et al., 2012). In the surveyed outcrop a cloud of $11*10^6$ points were detected (Fig. 3).

From the points cloud a fully rendered 3D geological model of the whole outcrop was generated, providing the possibility to extract the geometries of the structural discontinuities.

The 3D point cloud was converted in a mesh overlapped with the photos where the main discontinuity planes were manually targeted in order to locate the main rock mass fractures (Fig. 4).

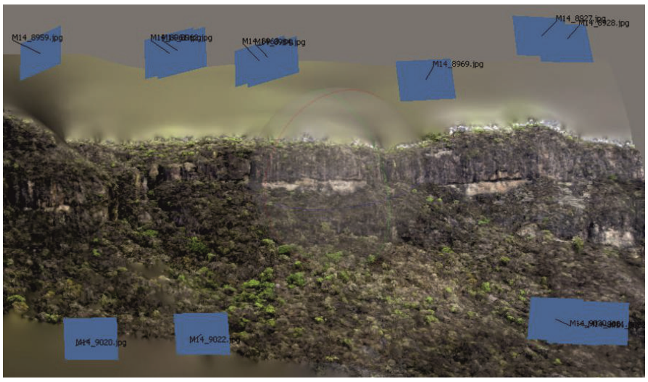

Fig. 3 – 3D points clouds of Chinipas cliff derived from the photos (frames) processed with the Structure from Motion algorithm.

The attitude of these discontinuities, expressed by dip direction and dip, was successively measured using a combination of GIS tools. The GIS procedure was developed in 4 steps: 1) detection of discontinuities traces, as the intersection line between fracture plane and topography; 2) these traces were converted into 3D point-features, using elevation data derived from the DEM; 3) raster surfaces interpolation of each 3D point-features group using the trend-analysis technique generating the flat surfaces corresponding to the discontinuity planes; 4) from each raster surface generated the two derivative slope raster map, (corresponding to discontinuity dip) and the aspect raster map (corresponding to discontinuity strike) were calculated.

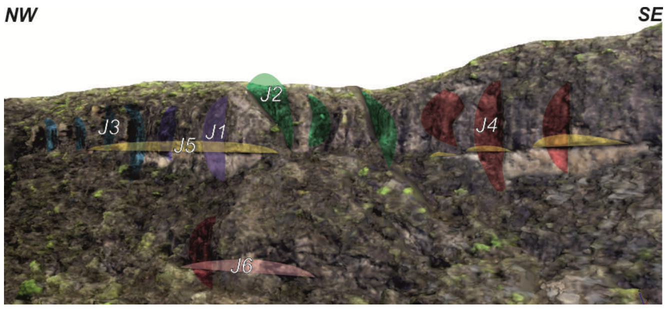

Fig. 4 – Main discontinuities of the rocky cliff identify on the virtual outcrop

RESULTS

The attitudes of the discontinuities acquired during the field survey and from remote sensing technique were processed through the classical spatial structural methods based on sterographic projections. The principal planes of the different joint systems were determinated on the single set and the density was calculated using the Fisher distribution. Both analyses allowed to identify the main discontinuities consisting of 6 systems of joints. Four mainly sub-vertical, oriented N-S, NNW-SSE, E-W and WNW-ESE, and two sub-horizontal, oriented E-W and NE-SW (Fig. 5).

We performed a comparison of results from the adopted techniques. Considering that the distribution of the attitude

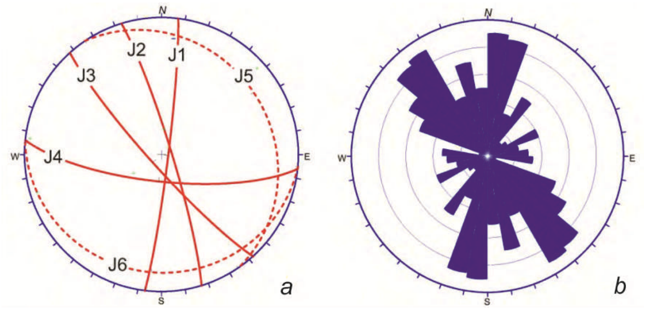

Fig. 5 – Main system of joint identify on the rocky cliff

values of the discontinuities should be interpreted in a statistical way, a simple analysis of difference in values seems provide acceptable results of ± 10° for dip direction and ±6° for dip (Tab.1).

The largest differences are related to the dip direction value

Joint set	M_DD	M_dip	V_DD	V_Dip	DD_Δ°	Dip_Δ°
J1	98	86	105	80	-7	6
J2	228	83	222	85	6	-2
J3	73	84	75	87	-2	-3
J4	185	15	172	10	13	5
J5	56	20	65	22	-9	-2
J6	186	74	178	73	8	1

Tab. 1 – Attitude (DD: Dip direction and Dip) values of main joint system (M: Measured; V: Derived from no-contact investigation).

of the lowest inclined surfaces, which are also the less exposed, especially if downward facing. The sub-vertical geometries are easier to detect both for the linear trace component and for the larger spatial geometries extension. It is important to remark that the fracture sets were identified manually from the reconstructed virtual outcrop. This procedure reduce bias due to the automatic detection caused by inaccuracies stemming from sparse sampling at scan edges, relatively thin mechanical beds at the border of the cliff, and obstruction due to vegetation or sharp bends along the exposure. Furthermore, the manual extraction method allowed to work directly with the raw data and enabled the operator to capitalize on *a priori* information of the fracture system at the cliff.

DISCUSSION AND CONCLUSION

Comparison of results shows that in remote area, where direct field surveys are time demanding and highly consuming in term of human and economic resources, it is possible to conduct a satisfactory identification of main system of discontinuities and following kinematic analysis and rock-fall modeling by means of remote sensing techniques and a combination of tool available in GIS environment. This approach allows in facts a quantitative estimation of the attitude of fractures delineated exploiting three-dimensional virtual reconstruction. Moreover, combining virtual reconstruction and GIS elaborations allows a significant increase in the number of fractures compared to those obtained during traditional field survey.

The method tested using two sources of information - remote 3D data and filed survey - showed a good adaptability to the different source of information. The case study here presented allowed us to validate the method and to provide a good base of data useful for the geomechanical and slope stability analysis. Our experience indicates that it is recommended to have a quite number of Ground Control Points (GCPs) in order to calibrate the image and increase the data precision.

The combination of the oblique SfM and zenital LIDAR point clouds in a GIS environment, represent a strong tool to analyse complex 3D structures. Finally, we emphasize that the proposed method can give a significant improvement in data acquisition only if the operators have a solid background in structural geology and rock mechanics.

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