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Monitoring of vertical cuts in soft rock mass, defining erosion rates and modelling time-dependent geometrical development of the slope

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ABSTRACT: Usage of Terrestrial Laser Scanners (TLS) is currently the best way of monitoring and detecting changes in slope morphology. In this study Optech ILRIS-3D was used. First scan of slope morphology with ILRIS-3D was made in March 2012 at presented pilot location "Žnjan" and it was repeated in 6 month intervals to this day. Series of observations in man-made cuts at additional 14 pilot sites using TLS were also made. For the purpose of forecasting and retrograde analysis, the survey was conducted in different time intervals and number of observations. Main goal of this monitoring was to define the average rate of erosion in cuts in this type of material. Also, a proper procedure for establishing future monitoring in this type of materials is introduced, as well as guidelines for selecting minimum and maximum time intervals. Finally, based on the results of monitoring, known mathematical model for development of erosion in cuts is calibrated and the guidelines for its usage are proposed.

1 INTRODUCTION

Marl from Eocene flysch strata, which can be found in Dalmatia region in Croatia, is just one example of soft rocks. Excavation in this type of materials could be performed only with the use of heavy machinery (rock breaker) or explosives. However, in a short time after excavation, in which the excavated cut in marl is exposed to influence of atmospheric agents, weathering process starts to affect material on the slope surface (Miščević & Vlastelica 2012). Repeated cycles of wetting and drying, heating and cooling, freezing and thawing, as parts of weathering process, can cause deterioration of marl into soil-like material. As a result of weathering, surface formed of weaker marl is eroded, and harder components of flysch can "stick out" on the slope surface like "cantilevers" (Fig. 1). In time, blocks of sandstone start to fall off the cut, and weathered marl is prone to both surface and deep sliding (Vlastelica 2015). Therefore, a suitable method for predicting these events is needed.

Each new insight into the processes that cause the instability of slopes can help to mitigate the consequences thereof. The development of new technologies in the field of geodesy, primarily LiDAR (Light Detection and Ranging) technology, opens new paths for monitoring changes in the earth's crust and the material from which it was created. These changes can be monitored on a global level, but also at the local level using TLS.

Figure 1. Example of differential weathering in flysch rock mass (Pilot site Trstenik, Split, Croatia).

LiDAR technology, combined with a variety of platforms (satellites, planes, helicopters, …) has developed into an indispensable tool for creating DEM models (Digital Elevation Model), and also for a range of applications in agriculture, archaeology, geology, mining, meteorology, etc. (NOAA 2012). With the development of portable variants, also known as TLS, which are more precise and within accessible price range, this technology found its application in monitoring the progress of erosion of slopes that were not available from aerial photographs (Lim et al. 2009, Dewez et al. 2009, Perroy et al. 2010). Figure 2 presents

Figure 2. Terrestrial laser scanner ILRIS-3D-ER on pilot site “Žnjan 1”.

terrestrial laser scanner ILRIS-3D-ER used in this study.

Using this technology it is possible to access the analysis of durability, not only through the classical laboratory techniques, but also “in-situ” to particular examples thereby valuing the actual changes.

2 WEATHERING AND EROSION

The term weathering (degradation, disintegration) usually represents a change in physical and mechanical properties of rocks as a result of peeling, hydration, weakening by drying and wetting (“slaking”), swelling, abrasion, freezing-thawing and other processes (Miščević 2004). Franklin & Dusseault (1989) use the term “weatherability” as a measure of susceptibility of a rock to weaken or decay in a period of time in which the construction is being used. In that sense, it is crucial to distinguish between:

- “engineering time scale” – a few years to several decades,
- “geological time scale” – hundreds of thousands to millions of years.

In soft rock, weathering process takes place in a very short period and one can speak of durability of the material within the “engineering time scale” – which corresponds to the period in which the construction is used (in this case – the cut in the slope).

The dominant process that causes degradation of marl (destruction of structural links within the material) in Dalmatia is repeated wetting and drying process, as a major cause of physical weathering, combined with chemical weathering on the surface of the material and the walls of cracks, i.e., all surfaces that are in direct contact with water (Miščević & Vlastelica 2011). Although formally separated, both processes usually occur simultaneously and are mutually complementary. Crack formation processes of physical weathering increases the surface on which chemical processes can be developed. On the other hand chemical weathering replaces solid minerals with weak clays or pores, which make material susceptible to physical weathering.

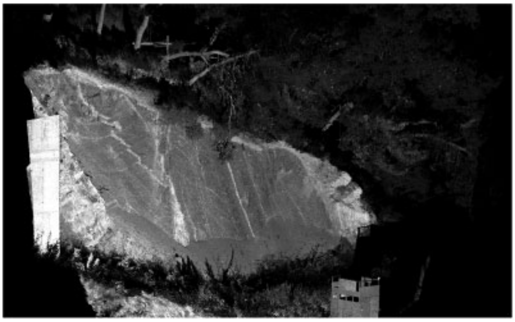

Figure 3. Example of point cloud with approximately 4 million points (pilot site “Žnjan 1”).

In order to truly understand the term weathering, it is necessary to define the concept of erosion, since the two terms are often confused. The difference between weathering and erosion is subtle, so it is easiest described as follows: *weathering breaks material into fragments, while erosion moves the fragmented pieces, from where they occurred to the place where they accumulate* (Vlastelica 2015). Of course, weathering and erosion can take place at the same time, so it is often conceptually mixed or erroneously considered synonymous.

With regard to the type of material and climatic features of the area of research, it is reasonable to assume that in Dalmatia region the ratio of processes varies in the range of balance of erosion and weathering, to an imbalance in favour of weathering. Therefore, erosion always occurs on the weathered material that constitutes slope surface of a cut.

3 METHODOLOGY

3.1 *Terrestrial laser scanning*

Terrestrial Laser Scanning (TLS) is a term for surveying by which it is possible to obtain large quantities of data (coordinates of points), unlike conventional surveying methods (i.e. total stations). In addition to the term TLS, the term frequently used is LiDAR (Light Detection and Ranging), which is usually associated with obtaining data from the air (e.g., using an aircraft as a platform) or the definition of the technology itself.

With TLS a large amount of processed data is obtained, which is called cloud of points (Fig. 3).

When checkpoints are referenced in the known coordinate system, then the whole cloud of points can be oriented in the same system. The points can be further specified with colour, i.e. RGB component can be defined and associated, when scanners have an integrated and calibrated digital camera (Kordić 2014).

The use of TLS in this work is presented solely from basic user’s perspective. For more information about the principles of measurement, technology and instrument performance reader is referred to additional literature (Petrie & Toth 2008, Teza et al. 2007, Kordić 2014).

3.2 *Comparison of point clouds from different epochs*

The change in morphology of cuts is carried out by comparing the point clouds from different epochs using the following methodology (Abellan et al. 2011, Lim et al. 2009):

- Obtaining a reference point cloud (Combine multiple point clouds in case of more scanning positions. Preferably georeferencing is done to determine spatial orientation of a cut).
- Creating a Triangle Irregular Network (TIN) model of the surface of the cut – reference surface (S_0).
- Obtaining new point cloud after a certain period (PC_1, PC_2, …, PC_n)
- Preparing the data for alignment between the multiple epochs.
- Comparing of the PC_i with the S_0.
- Calculating the difference for each different epoch.
- Creating cross-section for comparison or directly comparing point cloud with S_0 in 3D.

Preparation of data for comparison (4th bullet) between the series of measurements is defined by alignment matrix of the new point cloud with the reference surface. In this paper, the alignment matrix is defined by using a fixed object in the environment (buildings near of cuts or geological members which are not subject to weathering in engineering time scale), in following four steps:

- Identification of the stable part of the cut or an object in vicinity of the cut.
- Removal of the part of the point cloud where the changes take place (detachment and deposition) and any unwanted measurements (vegetation, moving objects, etc.).
- Alignment of the chosen stable part using Iterative Closest Point (ICP) algorithm, which defines the alignment matrix of the point cloud.
- Using the alignment matrix on the original point cloud.

Data collected by TLS can be analysed for the whole surface of the cut to give us a three-dimensional insight into the behaviour of the erosion process. Additional identification of the geological members of cuts, through photos and/or intensity of the returned laser beam, is a basis for further analysis of other phenomena, such as: landslides, rockfalls, toppling, etc.

Distance of each point in PC_i and S_0 is calculated using the "Data vs. reference comparison", (Polyworks v12), wherein the direction of comparison is determined by the direction of the vector perpendicular to the reference plane P_0. For the purpose of comparison of the data it is not necessary to execute georeferencing. In this case the origin point of the coordinate system is at the centre of TLS (O = 0, 0, 0). Distances D_i are calculated according to Abellan et al. (2010):

$$D_i = \text{Distance}[PC_i, O] - \text{Distance}[S_0, O] \tag{1}$$

D_i is the distance to be attributed to the separation and accumulation of material on slopes or the deformation of the slope in the form of rockfall (or movement prior to it). Some results can be attributed to the measurement error or errors in methodological approach therefore they must be carefully assessed (Vlastelica et al. 2014).

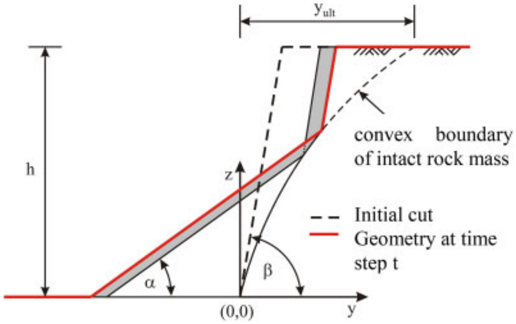

Figure 4. Fisher-Lehmann mathematical model of erosion of a vertical cut.

3.3 *Fisher-Lehmann mathematical model of erosion of vertical cuts*

This model is a combination of Fishers (1866) mathematical description of the degradation of abandoned, initially vertical, cuts in layers of chalk without accumulation of eroded material at the base of the cut, and Lehmann (1933) generalized model, which introduces the possibility of initial inclination of the slope and the accumulation of eroded material at the foot of the cut. The basic assumptions of this model (Figure 4) are:

- The slope is homogeneous.
- Surface of the cut is flat, tilted by angle β which is steep enough to allow erosion.
- The terrain at the foot and on the crest is horizontal and extends far enough.
- There is no standing water at the foot of the slope.
- In a given time, weathering products are steadily eroding from the free face. Larger landslides and separation by discontinuities are not considered.
- Weathering products accumulate in the foot of the cut in the form of talus with constant inclination α ($\alpha < \beta$).
- Under the accumulated rock talus there is no further weathering of the deposited material, while rock continues to weather and erode from the exposed free face. Ultimately it forms a convex boundary between the generated talus and intact rock mass.
- Finally, the cut is reshaped to a slope with inclination α as a tangent on the convex core of intact rock mass.

With the above assumptions, the expression for determining convex core of intact rock mass takes the following form (Hutchinson 1998):

$$y = k \cdot (l + m) \cdot \ln\left[\frac{m}{(m - z)}\right] - k \cdot z \tag{2}$$

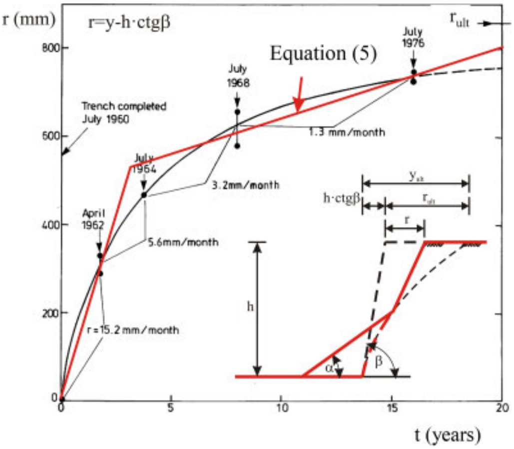

Figure 5. Annual erosion of "Overton Down" cut, UK (modified according to Hutchinson 1998).

where: $k = (a - ac - b)/c$; $l = b \cdot h/(a - ac - b)$; $a = ctg\alpha$; $b = ctg\beta$; $m = h/c$; h – height of the cut, α – talus angle and β – angle of the initial slope cut. The parameter c is a constant needed for exact derivation:

$$\frac{\text{rock volume}}{\text{talus volume}} = \frac{1-c}{1} \tag{3}$$

and it is a measure of permanent increase of volume.

Change in slope angle β can be described by introducing the following:

$$y(t) = \begin{cases} h \cdot ctg\beta & t = 0 \\ h \cdot ctg\beta + R_{y,s} & 0 < t < \left(y_{ult} - h \cdot ctg\beta\right)/R_{y,s} \\ y_{ult} & t \geq t_{ult} = \left(y_{ult} - h \cdot ctg\beta\right)/R_{y,s} \end{cases} \tag{4}$$

where $R_{y,s}$ is average annual erosion. According to Hutchinson (1998) erosion of a cut is not necessarily a linear process in time. On a 1.75 m high cut in chalk, based on occasional observations during the period of 15 years, he concluded that the process is non-linear (Fig. 5).

According to observations by Vlastelica (2015), it is possible to notice a very quick initial change in morphology of the cut, however it can equally be attributed to the initial stress redistribution in rock mass and local instabilities, which depend on the stratification and the quality of excavation.

Taking into account this observation, instead of the parameter $R_{y,s}$, a non-linear function $R_{y,s} = R_{y,s}(t)$ can be introduced, or the linear criterion described with expression (4) can be replaced with the bi-linear criteria:

$$y(t) = \begin{cases} h \cdot ctg\beta & t = 0 \\ h \cdot ctg\beta + n \cdot R_{y,s} & \text{if } 0 < t < t_1 \\ h \cdot ctg\beta + R_{y,s} & \text{if } t_1 < t < \left(y_{ult} - h \cdot ctg\beta\right)/R_{y,s} \\ y_{ult} & \text{if } t \geq t_{ult} = \left(y_{ult} - h \cdot ctg\beta\right)/R_{y,s} \end{cases} \tag{5}$$

where: n = coefficient of the initial relaxation of the cut; t_1 = period within the effects of initial relaxation of the cut. For example, in case of Hutchinson's cut (Fig. 5) these parameters would be n = 10 and t_1 = 3 years.

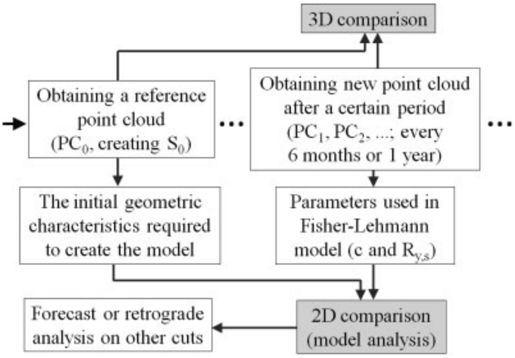

Figure 6. Flowchart presenting data-obtaining procedure and presentation of results.

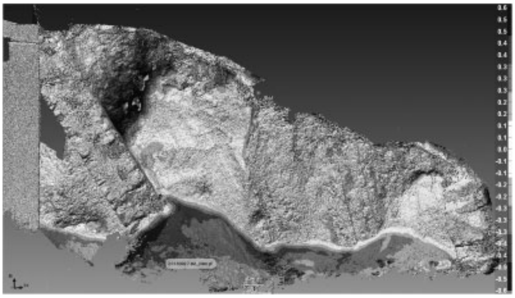

Figure 7. Comparison of point cloud PC_4 (10.3.2014.) with the reference surface S_0 (7.3.2012.) at pilot location "Žnjan 1".

4 RESULTS

In this paper result of comparisons of point clouds for one selected pilot site (pilot site "Žnjan 1", shown in Fig. 2 and 3) are presented. These comparisons can be displayed three-dimensionally as a field of differences in the face of cuts or two-dimensionally through selected representative cross-sections (Fig. 6).

In three dimensions the distances are shown through the field of values (Fig. 7). Negative values indicate a lack of material in a given epoch (erosion), or separation of larger rock fragments. Positive values indicate the accumulation of eroded material in the form of talus at the base of the cut or larger blocks due to rockfall. The positive shift towards the instrument, if it is in the open face of cuts, may indicate a displacement that preceded the rockfall.

Figure 8 shows the representative cross-sections as a result of observation during a period of 2 years (7.3.2012.–10.3.2014.), while Figure 9 shows the result of numerical calculation based on the Fisher-Lehmann model of erosion of the cut.

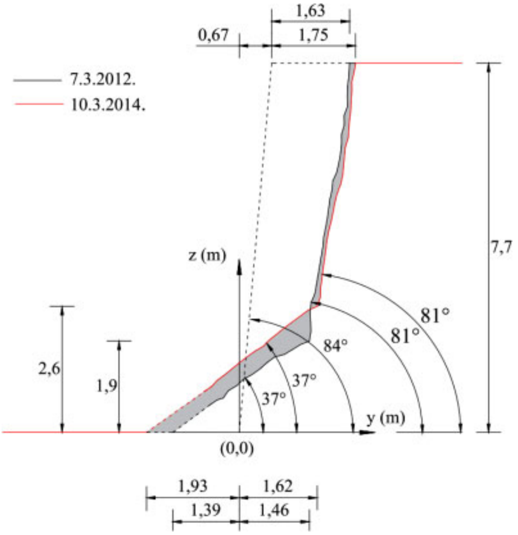

Figure 8. Results of observation carried out on pilot location "Žnjan 1". A typical cross-section of the epoch PC_0 and PC_4.

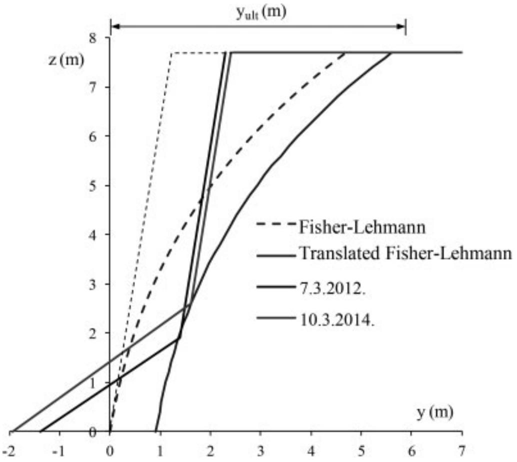

Figure 9. Fisher-Lehmann model based on the results of observations carried out on pilot location "Žnjan 1" (Fig. 8).

Field observation on this and other pilot sites reveals that, after the initial relaxation of cuts, Fisher-Lehmann model correctly describes the change in the profile of cuts in soft rocks that occur alone or in the flysch sequence in the area Dalmatia.

The parameters used for the calculation are presented in Table 1. All geometrical data were determined by the results of TLS on a representative cross-section. The calculation results by Fisher-Lehmann are presented in Table 2.

The curve of convex core of the intact rock mass, defined by expression (2), is in this case translated by 0.9 m to the left (Fig. 9). Reason for this translation lies in removing the deposited material on several occasions during the use of the plateau for the needs of nearby construction site.

Table 1. Parameters used in Fisher-Lehmann model for pilot location "Žnjan 1".

Parameter	α	β	h	c	$R_{y,s}$
	37°	81°	7.7 m	0.4	5.0 cm/year*

*$R_{y,s}$ is calculated as a three year average.

Table 2. Results of Fisher-Lehmann model for pilot location "Žnjan 1".

Parameter	Symbol	Result
Final position of crest	y_{ult}	4.96 m
Final position of foot of the talus	y_s	5.26 m
Final width of the slope	$y_{ult} + y_s$	10.22 m
Estimated time to the complete reshape of the slope (from 2014.)	$t_{ult} - \Delta t$	58 years
Estimated time to the complete reshape of the slope (from 2002.)*	$t_{ult} - \Delta t$	93 years

*The cut was originally excavated in 2002.

It is interesting to notice, when retrograde analysis is used, that the elapsed time between cutting and the current state would be $\Delta t = 35$ years, which does not correspond to the observed ($\Delta t_{real} = 12$ years; 2002.–2014.), which is due to the removal of deposited material realistically even shorter. On the other hand, the specified observation corresponds to Hutchinson's case study (Fig. 5) and the proposed bilinear criteria with which, for this pilot location, satisfactory results are obtained. For $n = 10$ and $t_1 = 3$ years, Δt is eight years. Due to the initial removal of deposited material, it corresponds exactly to the conducted field observation.

5 CONCLUSIONS

The amount of material which is eroded and disposed as talus beneath cuts and steep slopes is often impossible to determine accurately. The use of TLS enabled the subsequent detailed analysis of monitored cuts and selection of one or more representative profiles for geotechnical analysis.

For vertical cuts in flysch rock mass in Dalmatia region, couple of years after excavation, angles of free face of the cuts usually stabilize in the range of about 70° to 80°, except in cases where milder slope was selected by design. The slope of the talus ranges from 35° to 38°, regardless of the type of material or the ratio of the softer and harder geological members in flysch sequence. Average annual erosion on observed 14 pilot locations ranged from 3 to 7 cm/year (average of 5 cm/yr), up to 10 cm/year for coastal cliffs. These values are only rough guidelines, established on multiple profiles for each selected location as the average value for a short period of observation. Locally higher values can occur.

By using this data it is possible to provide retrograde analysis for existing cuts, or to forecast the time needed for complete slope reshaping in the form of talus. In this paper Fisher-Lehmann mathematical model is tested. It can be concluded that results correspond to field observations, except in the first couple of years after the cut is made. This limitation can be attributed to initial stress redistribution in rock mass and local instabilities, which can depend on the stratification and the quality of excavation.

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REFERENCES

Abellan, A., Calvet, J., Vilaplana, J. M., Blanchard, J. 2010. Detection and spatial prediction of rockfalls by means of terrestrial laser scanner monitoring. *Geomorphology*, 119 (3–4), 162–171.

Abellan, A., Vilaplana, J. M., Calvet, J., Garcia-Selles, D., Asensio, E. 2011. Rockfall monitoring by Terrestrial Laser Scanning – case study of the basaltic rock face at Castellfollit de la Roca (Catalonia, Spain). *Nat. Hazards Earth Syst. Sci.*, 11, 829–841.

Dewez, T., Gebrayel, D., Lhomme, D., Robin, Y. 2009. Quantifying morphological changes of sandy coasts by photogrammetry and cliff coasts by lasergrammetry. *La Houille Blanche*, 1, 32–37.

Fisher, O. 1866.: On the disintegration of a chalk cliff, *Geological Magazine*, 3, 354–356.

Franklin, J.A., Dusseault, M.B. 1989.: *Rock Engineering.* McGraw-Hill, New York, 600 pp.

Hutchinson, J.N. 1998. A small-scale field check on the Fisher–Lehmann and Bakker–Le Heux cliff degradation models. *Earth Surface Processes and Landforms* 23, 913–926.

Kordić, B. 2014. *Development of three-dimensional terrestrial laser scanning method for determining and analyzing of landslide surface movements.* Zagreb: University of Zagreb, Faculty of Geodesy. PhD thesis.

Lehmann, O. 1933. Morphologische Theorie der Verwitterung von Steinschlagwänden. Zurich: *Vierteljahrsschrift der Naturforschende Gesellschaft*, 78, 83–126.

Lim, M., Rosser, N. J., Allison, R. J., Petley, D. N. 2009. Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire. *Geomorphology*, 114(1–2), 12–21.

Miščević, P. 2004. *Introduction to rock mechanics. (In Croatian)* Split: University of Split, Faculty of Civil Engineering.

Miščević, P. & Vlastelica, G. 2011. Durability Characterization of Marls from the Region of Dalmatia, Croatia. *Geotechnical and Geological Engineering*: 04/2012; 29(5):771–781.

Miščević, P. & Vlastelica, G. 2012. Time-dependant stability of slopes excavated in marl. *Građevinar* 64, 6; 451–461

National Oceanic and Atmospheric Administration (NOAA), Coastal Services Center 2012. *Lidar 101: An Introduction to Lidar Technology, Data, and Applications.* Revised. Charleston, SC: NOAA Coastal Services Center.

Perroy, R.L., Bookhagen, B., Asner, G.P., Chadwick, O.A. 2010. Comparison of gully erosion estimates using airborne and ground-based LiDAR on Santa Cruz Island, California. *Geomorphology* 118, 288–300.

Petrie, G., Toth, C.K. 2008. Introduction to laser ranging, profiling and scanning. In:Shan, J., Toth, C.K. (Eds.), *Topographic Laser Ranging and Scanning: Principles and Processing.* CRC Press / Taylor & Francis, London, pp. 1–28.

Teza, G., Galgaro, A., Zaltron, N., Genevois, R. 2007. Terrestrial laser scanner to detect landslide displacement fields: a new approach. *Int. J. Remote Sens.* 28, 3425–3446.

Vlastelica, G. 2015. *The Influence of Weathering on Durability of Cuts in Soft Rock Mass.* Split: University of Split, Faculty of Civil Engineering, Architecture and Geodesy. PhD thesis.

Vlastelica, G., Miščević, P., Fukuoka H. 2014. Rockfall Monitoring by Terrestrial Laser Scanning – Case Study of the Rock Cliff at Duće, Croatia. *Landslide and Flood Hazard Assessment, Proc. of the 1st Regional Symposium on Landslides in the Adriatic-Balkan Region* Mihalić Arbanas S.; Arbanas Ž. (ur.). Zagreb: Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb and Faculty of Civil Engineering, University of Rijeka, 2014. 51–55.