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ORIGINAL PAPER

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COMPLEX GEODETIC AND PHOTOGRAMMETRIC MONITORING OF THE KRAĽOVANY ROCK SLIDE

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ABSTRACT

Purpose	The complex monitoring of rock slides with the size of 16 ha in order to predict the development of other slides and prevent possible human and material losses.
Methods	Precise geodetic point measurement, terrestrial laser and image scanning and aerial photogrammetry were used to obtain detailed knowledge about the geometry and behaviour of the rock slide. Except for terrestrial images, the images were taken using an SLR camera (set on a motor paraglide) and a compact camera (set on a remotely piloted system). The state and condition of the locality before the rock slide was taken from archive images taken by a digital large format camera.
Results	Vectors and velocities of the displacements of discrete points were determined with high precision; the changes in quarry wall surfaces were determined by laser and photogrammetry scanning. Finally, high resolution orthophotomosaics of the site were generated using aerial photogrammetry at each observation point.
Practical implications	The termination of mining and the design of the remediation works were determined according to the results of the measurements. Also, monitoring was carried out in order to observe any changes due to the implementation of a highway project based in the localisation.
Originality/ value	Complex geodetic and photogrammetric monitoring of rock slides offers detailed information about slide surfaces and has previously been used in Slovakia on a significant scale.

Keywords
rock slide, laser and image scanning, RPAS photogrammetry

1. INTRODUCTION

The Kraľovany rock slide, which took place in the active limestone quarry (Fig. 1) in the spring of 2013, is one of the most spectacular slope failures in the modern history of Slovakia, both in terms of its dimensions as well as the risk posed to society. It has reached a width of 570 m and a length of 280 m; the volume of the sliding mass has exceeded 2 million m^3 and the daily average sliding speed is 1 cm.

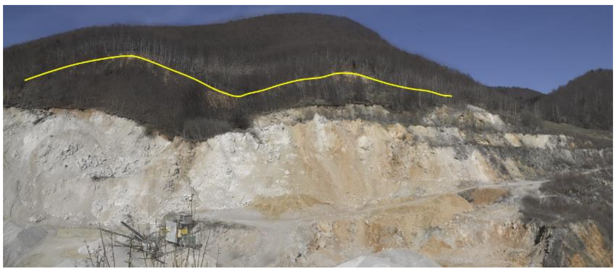

Fig. 1. Southern view of the quarry head scarp

The predisposition for sliding created the presence of tectonic failure in the form of over thrust line with accompanying mylonitization and further alterations (Šimeková et. al., 2013). The main triggering factors were excessive precipitation in the winter season of 2012/2013 in combination with snow cap melting in spring 2013, and the quarrying of raw materials – limestone and dolomite – in the frontal part of the slide which had been ongoing for over five decades. The locality is, in terms of risks to safety, of interest for two reasons – first, under the eastern part of the rock slide there is a lake (Fig. 2 in the bottom-middle of the image), which is visited by tourists and holidaymakers, and second, the D1 motorway project passes through the territory of the rock slide (section Dubná Skala – Turany – Hubová – Ivachnová).

This situation required immediate action from engineering geologists from the State Geological Institute of Dionýz Štúr and the Slovak University of Technology. The investigation of the slide was comprised of engineering geological mapping and geodetic monitoring (Liščák & Fraštia, 2014).

Fig. 2. Top view of the rock slide, its head scarp and arrangement of the observed points. The most active part of the rock slide is highlighted in white shading

This study made use of different geometry measurement techniques such as terrestrial and GNSS methods, terrestrial and aerial photogrammetry and laser scanning to produce reliable data concerning slide behaviour.

2. METHODOLOGY OF MEASUREMENTS AND DATA PROCESSING

Several geodetic and photogrammetric methods of displacement observation have been used to ensure the comprehensive evaluation of rock slide kinematic activity. They are both selective method (point) measurements, which are characterized by high precision but low levels of detail and by unselective (surface) methods of data acquisition, which document the entire measured area with a high density but, on the other hand, with lower accuracy. To compare the current state of the slide to its previous states aerial images taken in August 2010 and the coordinates of the highway network pillars measured in July 2010 were used. After slide began several types of measurement were carried out using several methods (Table 1).

Table 1. Surveying activities schedule

Date	Subject/measurement technology
July 2010	Points of the network
21.08.2010	Imagery by UltraCam Xp camera
Spring 2013	**Activation of the rock slide**
14.05.2013	Points of the network
23.05.2013	Points of the network and supplementary monitoring points
29.05.2013	Points of the network and supplementary monitoring points Terrestrial laser scanning of the quarry Photogrammetric measurements
2.07.2013	Points of the network and supplementary monitoring points Photogrammetric measurements
14.08.2013	Points of the network and supplementary monitoring points Photogrammetric measurements
22.08.2013	Terrestrial laser scanning of the quarry
21.03.2014	Points of the network and an additional point of monitoring Terrestrial laser scanning of quarry Photogrammetric measurements
25.04.2014	Points of the network and supplementary monitoring points Terrestrial laser scanning of the quarry Photogrammetric measurements
26.05.2014	Points of the network and supplementary monitoring points Terrestrial laser scanning of the quarry Photogrammetric measurements

2.1. The selective measurement technique

The monitoring points are:
1. Points of the highway network – sheeted pillars with deep stabilization.
2. Geoharpoons stabilized by iron bars up to a depth of 0.5 m. The reference network frame provided information concerning the pillars outside the rock slide zone.

Precise point measurement was carried out using the **spatial polar method** using a total station (TS) LEICA TS30, and prisms on the pillars or on a telescopic rod with a bipod and vial (geoharpoons – points labelled "B") or retro-reflective markers. The LEICA TS30 has declared mean angle measurement error of 0.5", the accuracy of the distance measurements to the prism is 0,6 mm + 1 ppm, the accuracy of the distance measurements of the reflective label is 1 mm + 1 ppm and for the distance measurement to the natural surface it is 2 mm + 2 ppm. The configuration of the monitored points is shown in Figure 2.

The processing of the network was carried out separately by position and by height in the following ways:
1. The adjustment of the local geodetic network with a scale coefficient of 1.000000.
2. 2D similarity transformations of the adjusted network to the JTSK03 system using identical reference points of 550, 638 and 690. This ensured the correct scale of the network in the JTSK03 system and the positional stability of the reference points to be verified. The control point is observation point number 688, which appears to be statistically stable.
3. The calculation of the elevations of the observation points by least square method adjustments.
4. The calculation of differences at different epochs.

Positional processing consisted of estimating the coordinates of points using a second linear statistical model. The actual statistical estimate was carried out using the least squares method as a free network. The physical reduction of the measured distances (due to temperature, pressure and humidity) was introduced directly whilst the measurements were being carried out. The average standard error of the adjusted direction was less than 3cc and the average standard error of the adjusted distance was less than 2 mm and this was obtained by carrying out positional adjustments to the network in each time period. The standard error of coordinates did not exceed 2 mm for the X and Y axes. The observational plan is shown in Figure 3.

The similarity transformation of the local coordinates of the adjusted network for every epoch to epoch realization in the year 2010 did not exceed a mean coordinate error of 4.5 mm at identical points in each epoch, while the coordinate residuals at reference point no. 688 did not exceed 2 mm (this point was not included in the computing of the transformation parameters). The network scale derived from transformation does not differ from the exact value (0.999840) of reduction from JTSK projection and zero equipotential surfaces of more than 1 mm/100 m at each epoch.

The verification of positional stability of the reference points. From the residuals observed after the similarity transformation and scale factor value, we can conclude that the point trio 550-638-690 lying outside the rock slide area has been proven to have positional stability. This has also been