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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.

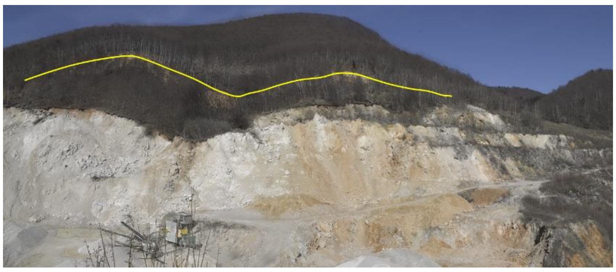

Fig. 1. Southern view of the quarry head scarp

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).

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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 confirmed by GNSS measurements. Additionally, point no. 688 situated outside the rock slide area does not show a statistically significant positional change and serves as a reference point.

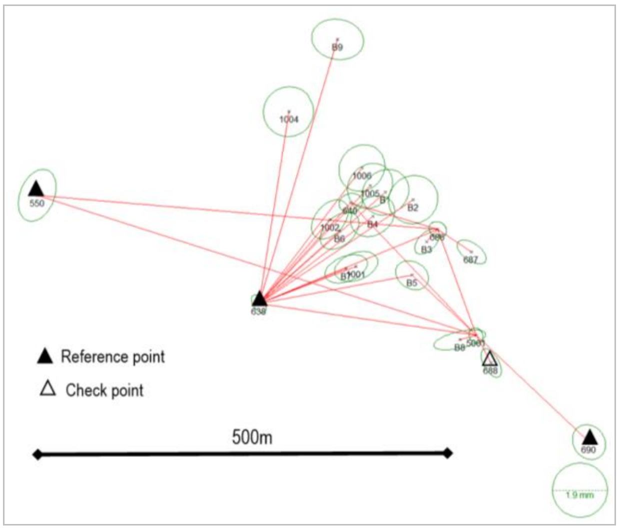

Fig. 3. Observational plan and standard error ellipses

The elevation stability of the reference points is verified on the basis of height accuracy determined using a trigonometric method. Elevation angles have been corrected to take into account index error and reduced for the correction of refraction and the curvature of the Earth. Since the measurement heights was overestimated, the height network was adjusted using the least squares method. Standard errors in the height of the points did not exceed 2 mm. However, as elevations were measured by primarily using one method, a reasonable estimate of the standard error of the estimated heights of points is mH = ±10 mm in relation to the nearest reference point (no. 638).

Global Navigation Satellite System (GNSS) measuring technology was used, primarily, to measure the position and elevation of reference points as well as the epoch measurement of the observed points between the epochs measured using a total station. The length of the observations of the reference points was at least 2 hours and of the observed points approximately 30 minutes. The measurements were processed as static in post-processing mode. The accuracy of the apparatus was not more than 3 mm + 1 ppm, but some points did not permit optimal measurement conditions in terms of elevation mask, as they were placed near vegetation cover or a steep slope.

2.2. Non selective measurement techniques

Information about the geometry of the surface observed throughout the site provide us with scanning methods, which recorded points of the surface with a spacing of several centimetres or decimetres, these points are usually processed into a detailed digital elevation model. During this study, the technologies used were terrestrial laser scanning (TLS) and digital photogrammetry – image scanning (Pukanská, 2013).

Terrestrial laser scanning. The walls of the quarry and surrounding land were scanned by the terrestrial laser scanner RIEGL VZ-400 with a range of 600 m (at 90% reflectivity), the scanning speed mode with long range measurement reached 42 000 points per second and the spatial standard error of the measured points m_{XYZ} equalled 5 mm (related to the scanner station). It must be noted that the quarry surface created by rock is ideal for the reflectance of the laser beam, on the other hand, vegetation (grass, shrubs and trees) distorts digital elevation model significantly. The areas of the Kraľovany rock slide that do not have vegetation are, mostly, in the accumulation and head scarp areas. TLS scans include, in every epoch, about 100 million points in the scanning resolution of 0,03 m/100 m. Point clouds (Fig. 4) were processed into TIN models.

Fig. 4. Coloured point cloud from laser scanning, South view

Digital Photogrammetry. The other piece of scanning technology used was digital photogrammetry, namely the method of image scanning (Trhan & Fraštia, 2014). Both aerial and terrestrial images were used. Aerial images were taken using a plane, motor paraglide and an unmanned aerial vehicle – Aibot X6 (Aibotix n.d.).

The images taken by the UltraCam Xp camera (Fig. 5) show archival material from August 2010 and serve as a comparison of the situation of the rock slide site prior to its beginning. Stereoscopic images with 60% longitudinal overlap were processed into a digital elevation model (Fig. 6) and a georeferenced orthophotomosaic (Fig. 7). The image resolution is 17310 × 11310 pixels and it achieves spatial resolution of 0,25 m on the ground (GSD).

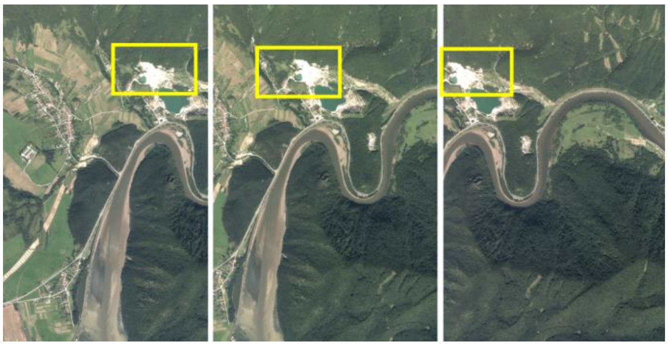

Fig. 5. Series of stereoscopic images taken by the UltraCam Xp large-format camera (2010) used to create DEM and an orthophotomosaic. The rock slide can be seen in the yellow boxes

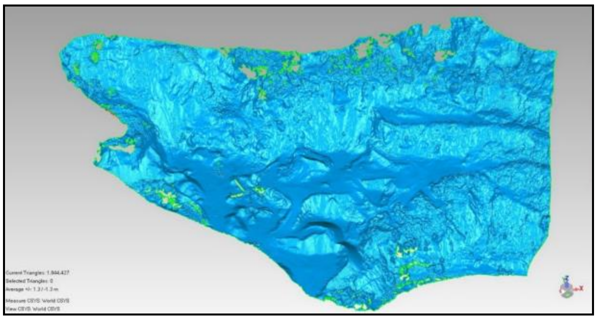

Fig. 6. Digital elevation model of the quarry

Fig. 7. The georeferenced orthophotomosaic (2010) with a resolution of 0,25 m per pixel

From the terrestrial images taken from the opposite (southern) slope it was possible to generate a digital model and orthophotomosaic with a resolution of 0,05 m/pixel (Fig. 8), or higher, as appropriate. This material is used primarily for the visual assessment of the state of the quarry walls. Scanning was performed using a medium-format camera, Mamyia with a 33 MP digital back LEAF Aptus II-7 and a PhaseOne 45 mm lens (Table 2). Some of the points of laser scanning served as control points for the photogrammetry.

Table 2. Technical specifications of the camera used and its accessories

Mamyia 645AF – LEAF Aptus 7-II – PhaseOne f45mm			
Number of pixels	33 000 000	Data format	TIFF
Format of CCD sensor	36 × 48 mm^2	Resolution	6666 × 4992
Focal length	45 mm	Image scale	–
Pixel size	7,2 μm	Lenses	PhaseOne f45/2,8

Fig. 8. Orthophotomosaic with a resolution of 0.03 m per pixel, southern view (projection plane XH)

3. RESULTS AND DISCUSSION

The results obtained from the measurements enabled the determination of the size and direction of displacements at discrete points and the changes in the observed profiles or surfaces. The displacements of the observed points or surfaces were evaluated on the basis of shift magnitude and its standard error. To test the statistical null hypothesis "displacement occurred" we can use the following simplified interpretation (Table 3), which is sufficient for the majority of practical geodesy tasks (p – displacement, mp – standard error of displacement, i – number of epoch):

Table 3. Decision concerning displacement using the confidential coefficient 2.5

If	$p_i \le mp_i$	then	hypothesis that displacement occurred is rejected
	$mp_i \le p_i \le 2{,}5^* mp_i$		hypothesis that the displacement occurred is not rejected, but the risk is relatively high
	$2{,}5^* mp_i \le p_i$		hypothesis that the displacement occurred is confirmed with a risk of less than 1%

There are limit values of displacements in the last column of table 4, which can be considered statistically significant, i.e. the displacement occurred if these values were exceeded.

Table 4. The accuracy of the measurement methods and the evaluation of hypothesis concerning displacements

Measurement method	Standard error	Standard error of displace-ment	Displacement occurred with a probability of more than 99% when
Geodetic measurements by Total Station			
Position XY – pillars	$m_x = m_y = 3$ mm	5 mm	p ≥ 12 mm
Position XY – geoharpoons	$m_x = m_y = 5$ mm	7 mm	p ≥ 20 mm
Height H – pillars and geoharpoons	$m_H = 7$ mm	10 mm	p ≥ 25 mm
GNSS static			
Position XY – pillars	$m_x = m_y = 5$ mm	8 mm	p ≥ 20 mm
Position XY – geoharpoons	$m_x = m_y = 7$ mm	10 mm	p ≥ 25 mm
Height H – pillars and geoharpoons	$m_H = 15$ mm	22 mm	p ≥ 56 mm
Terrestrial Laser Scanning			
Terrain surface	$m_{xyz} = 10$ mm	14 mm	p ≥ 35 mm
Photogrammetry – Ultracam Xp			
Orthophotomosaic	$m_{xy} = 0.25$ m	0.35 m	p ≥ 0.75 m
Elevation model	$m_H = 0.38$ m	0.53 m	p ≥ 1.20 m
Photogrammetry – UAV, Motor Paraglide			
Orthophotomosaic	$m_{xy} = 0.05$ m	0.07 m	p ≥ 0.17 m
Elevation model	$m_H = 0.10$ m	0.14 m	p ≥ 0.35 m
Photogrammetry – terrestrial			
Orthophotomosaic (vertical southern view)	$m_{xy} = 0.03$ m	0.04 m	p ≥ 0.10 m
Elevation model (only quarry walls)	$m_H = 0.05$ m	0.07 m	p ≥ 0.17 m

The maximum displacements of the upper edge of the quarry in the direction of axis X against the 2010 epoch ranged from approximately 20 to 40 m (Fig. 9) in the most active western part, with relation to the extent of the uncovered rock below the head scarp (Fig. 11). Network point no. 640 in the eastern part changed position in the direction of axis X by 5.6 m and even increased its elevation to 1.0 m (over a period of 17 months). While the western part of the rock slide shows movement toward the south, the eastern part is heading southwest. The speed of the changes in the most active (western) part is about 50 mm per day (during the observation epochs). Points on the eastern edge of the observed locations (no. 688 and B8) show good stability, but points westward at the front of the slide are demonstrably displaced – B5 (28 mm) and B6 (40 mm). Point B7 on the shore of the large lake has not exceeded the critical value of displacement yet but it is currently at the limit value. Displacements are graphically presented in the profiles (Fig. 10).

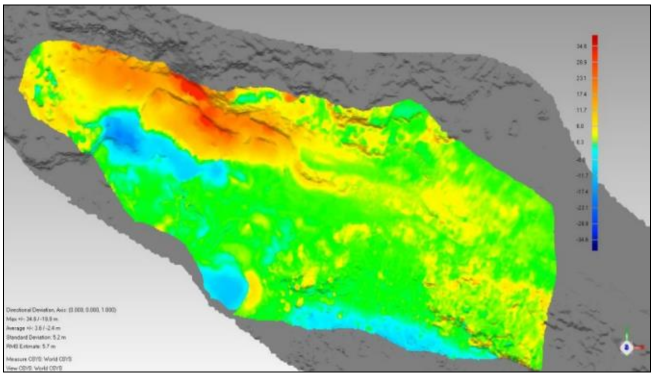

Fig. 9. Surface comparison of TIN models from 2010 and May 2013, top view. Green – no displacements, red – displacements of up to 34 m in the direction of the rock slide, blue – material which has been removed from the quarry

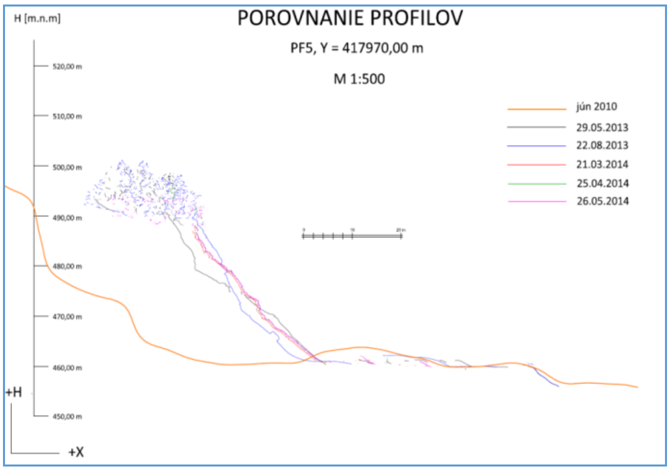

Fig. 10. Comparison of the development of the rock slide quarry walls in profile (graphical scale bar – 20 m)

Fig. 11. Uncovered rock (shear surface) under the head scarp of the slide

4. CONCLUSIONS

The issue of the sliding processes requires the cooperation of experts from a range of geoscience fields. Surveyors primarily document the manifestations of the geometric changes on the terrain surface. Point measurements of stabilized and signaled points have been mainly used. Such monitoring methods do not provide an overview of the whole observed area, moreover, the stabilization of observed points is expensive, although it should be noted that these measurements are the most accurate (if radar measurements are not considered). TLS, which is a highly efficient method of site documenting throughout a whole area, is able to reliably detect changes at a level of about 30–50 mm. The limitation of TLS is that it does not capture areas that are in occultation, especially horizontal surfaces above the station of the scanner. In this case, aerial photogrammetry can record this "hidden" information and supplements the whole mosaic of the surface geometry. In addition, one of the outputs of photogrammetric methods is an orthophotomosaic, which provides unique information about the site. Finally, using archival images, information can be obtained concerning the status of the site prior to the sliding. Such comprehensive monitoring can significantly simplify and make engineering geological interpretation of the causes and development of the slide as well as its remediation design more accurate.

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References

Šimeková, J., Liščák, P., Kopecký, M., Fraštia, M., Ondrejka, P., Žilka, A, Kováčik, M., Pauditš, P., Balík, D. (2013). Monitoring pohybovej aktivity havarijného skalného zosuvu v obci Kraľovany [Monitoring of move activity of emergency rock slide in Kraľovany village]. *Geologické práce, správy*, (122), 7–27.

Liščák, P., Fraštia, M. (2014). Kraľovany Rocksilde – its tectonical predisposition and kinematics. In *Geologi for Samfunnet (Geology for Society). NGU Report 2014.030, 3rd Slope Tectonics conference – Program and abstrakt book* (p. 38). Trondheim: Geological Survey of Norway.

Pukanská, K. (2013). *3D visualisation of cultural heritage by using laser scanning and digital photogrammetry* (1st ed.). Ostrava: VŠB – Technická univerzita.

Trhan, O., Fraštia, M. (2014). Skúsenosti zo spracovania údajov v aplikáciách PhotoScan a UAS Master [Experiences from data processing in applications Photoscan and UAS Master]. In *Technológie priestorového modelovania krajiny a objektov – prístupy a aplikácie* [electronic source] (p. 14). Bratislava: STU.

Aibotix (n.d.). Retrived 12.12.2014, from http://www.aibotix.com/