Monitoring of landslide dynamics with LIDAR, SAR interferometry and photogrammetry. Case study of Kłodne landslide (Southern Poland)

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Abstract The Kłodne landslide is located in the central part of Polish Carpathians in Beskid Wyspowy Mountains, east of the city of Limanowa. On June 1st 2010 after heavy and long-lasting rainfalls the Kłodne landslide was triggered affecting the area that was considered as stable. Most of the landslide movement occurred within few days and destroyed 17 houses and two farm buildings.

With the example of Kłodne landslide the authors compare the airborne data acquired prior to the landsliding (aerial sterophotograps and photogrammetric DEM) with newly acquired data (aerial photographs and LiDAR DEM) of July 2010. The analysis allows to measure horizontal and vertical displacements and roughly estimate the volume of the colluvium.

High Resolution satellite SAR (Synthetic Aperture Radar) data acquired by TerraSAR-X system were used for interferometric analysis to measure the small scale displacements that occurred in different parts of the landslide. The further monitoring of Kłodne landslide activity is continued using repeated terrestrial laser scanning campaigns.

Keywords Carpathians, Kłodne landslide, laser scanning, SAR interferometry, photogrammetry,

Introduction

On the night of June 1, 2010, in the village Kłodne near Limanowa (Fig. 1) after heavy and long-lasting rain, a landslide has been activated covering an area of 29 ha. Signs of the movement of landslide were observed on the day before, in the form of cracks and loss of stormwater runoff on slopes. In the first stage of the activity, the landslide has destroyed 17 homes and farm buildings and infrastructure network. Terrain surface of the area was heavily deformed. The landslide has been formed in the close vicinity of known and already mapped old and large (71.5 ha) landslide, and therefore in the initial stage of the research, it was thought that the observed activity is associated with reactivation of this particular landslide. Then, the number of questions were rise, the solution of which will be found during the study of the landslide activity in Kłodne. The aim of this study was to answer the following questions: Is the landslide is new, or just an activated part of an ancient larger form? What deformation occurred during the main landslide? What is the dynamics of the landslide at a later stage ?

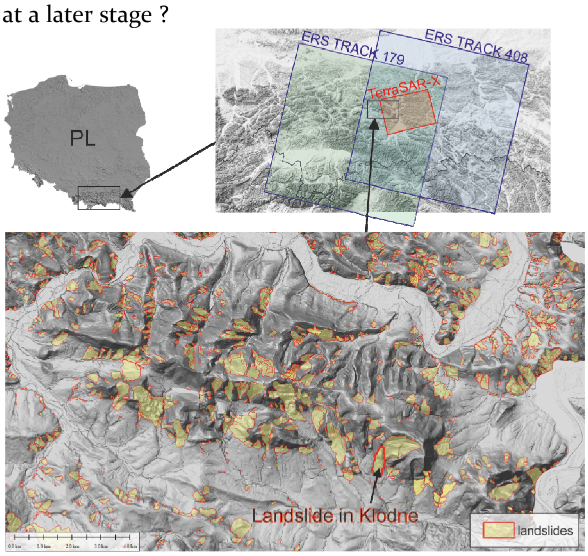

Fig.1. Location of Kłodne landslide associated with landslide inventory map of the area and extent of SAR data used In this project

Landslide in Kłodne become the perfect testing ground for a number of methods. Photogrammetric techniques were used with archival aerial photographs to get the Digital Terrain Model (DTM), terrestrial laser scanning used for acquisition of four sessions and aerial laser scanning were performed. Landslide activity was further measured using satellite radar interferometry using ERS SAR archival data and contemporary, high-resolution data from TerraSAR-X satellite. The measurements were supplemented by repetitive measurements of control points using GNSS technology. All information collected by different methods were integrated in GIS, and their analysis helped to characterize the activity of the Kłodne landslide.

Kłodne landslide – geology and geomorphology

Landslide occurs on the southern slope which is located in the eastern part of the Jaworz Ridge in Beskid Wyspowy (Starkel, 1972). It is an area susceptible to mass movements, which is facilitated by flysch-type geology of the area. The upper part of the Jaworz – Chełm synclinal ridge is composed of thick-bedded Magura sandstones (upper Eocene), which are located in fine sandstone and slate layers of mid-bedded Hieroglyphic (upper Eocene) and variegated shales (middle Eocene). These sediments are strongly folded and cut by faults. Landslide of the upper part resulted exposure of bedrock that in which fault of meridian trending was visible. Landslide, whose length is 1050 m and a width of 460 m, has been thus created in tectonically deformed flysch sediments. After the catastrophic rains, water-soaked sandstone exerted tremendous pressure on the slate layers, and then after crossing the shear strength, the landslide occurred, which completely destroyed the buildings on the slope.

Landslide should be classified as rock-complex (Varnes, 1978), where the upper part is a consequent, while the bottom layer of the substrate are passed obsequently to the slopes. The characteristic forms of landslides are the main scarp now reaching four meters high, a large extensional crack (ditch) and large, transverse, accumulation ridge in the central part of the landslide, reaching 35 m in height. In this section, there are also a number of open joints and caves. The foot of the landslide has strongly rippled surface with depressions and ruptures. The estimated depth of the landslide can reach 42 m.

The input data used

The aim of this study was to determine the condition of the slope prior catastrophic landslide, then the measurement of the main deformation and subsequent monitoring of further landslide activity after the main event. To perform these tasks, available archival data and newly acquired have been used.

The analysis of archival data includes the interpretation of topographic maps scale of 1:10 000 and photogrammetric analysis of the pair of aerial photographs taken in 2004 and 2009 on a scale similar to the 1:13 000. Using Intergraph photogrammetric station, numerical terrain models were generated with a resolution of 1 m. In order to check the potential activity on the slopes in the past, SAR interferometry with ERS-1/2 data was applied. Two data stacks of 179 track (51 scenes) and track 408 (49 scenes) covering the period between 1992 to 2000 were processed (Fig.1).

After the occurrence of Kłodne landslide, the efforts were made to acquire the new data. On July 2, 2010, at the request of Polish Geological Institute-National Research Institute (PGI-NRI), the MGGP Aero company acquired the airborne laser scanning data of a density of 4 pts/m2, with RIEGL LMS-Q680i scanner (Borkowski et al., 2011). Simultaneously, digital aerial photographs of 15 cm resolution were recorded. In addition, the terrestrial, surficial monitoring of the landslide has been initiated by PGI-NRI at 6-months intervals measurement sessions. It consists of a ground-based laser scanning with RIEGL VZ-1000 and RIEGL LPM-321 instruments and GNSS measurements on stabilized points on the landslide surface. To date, five test sessions between: 11.05.2011 and 09.07.2013. Application of laser scanning for landslide research was already described (Jaboyedoff et al., 2010). SAR interferometric study have been continued and new acquisitions of high resolution TerraSAR-X satellite have been ordered. 20 SAR StripMap images have been acquired covering the period from 6.10.2010 to 13.06.2012 (Fig.1).

The results of the Kłodne landslide study

Slope condition before 01/06/2010

Stereoscopic interpretation of archival aerial photographs did not show the existence of any landslide forms by 2010 at the analyzed slope. However, the evidence of older landslides located nearby was found. On both data sets from 2004 and 2009, the mentioned area was characterized by a smooth surface, cultivated agricultural or forest -covered. Possibly, the consequent layout of the rock layers in the upper part of the slope suggests that in the past small landslides may occur but there is no evidence of any deformation and relief forms in the record of aerial image. These movements, however, have to be detected in the calculated terrain elevation difference or show a small object shifting occurring there. Based on Digital Terrain Models (DTM) generated from aerial photographs, the differential model showing the changes occurred between 2004 and 2009 was calculated. This analysis showed no surface deformation, and the only differences found were due to differences in forest vegetation.

Also SAR interferometric analysis performed on the archival SAR scenes acquired by ERS-1/2 satellites from 1992 to 2000 yr did not show any activity in the particular area. The analysis were done with MTI (Multi Temporal InSAR) method with StaMPS algorithm (Hooper, 2008) using both PSI (Hooper et al., 2004) and SBAS (Berardino et al., 2002) approaches independently for the two data stacks from tracks 179 and 408. In each of the sets of received PS points, represent at least a few objects located within a landslide today. None of these points, however, showed no changes that could be identified as a deformation associated with landslide.

Given these results, it can be assumed that the landslide in Kłodne created on 1 June 2010, is a completely new landslide.

Main deformation of landslide

Landslide in Kłodne was very dynamic in the first week of its history. Horizontal displacement reached 85.6 m in upper part landslide, 65 m in the center and 50.5 m in the lower part (Fig. 2). The magnitude and directions of these displacements were calculated by comparing the position of field objects (buildings, intersections) on aerial photographs acquired in 2009 and 02.07.2010. Movement of the upper part of landslide was facing SSE, the middle part was sliding towards the West, while the lower part to the south (Fig. 2). The complex system of the movements is probably due to the complex nature of the shear plane which was controlled by the complex geological structure.

The spatial pattern of vertical displacement (Fig. 2) were obtained by comparing the photogrammetric DTM from 2009 with LIDAR-based DTM from 02.07.2010. The largest subsidence reaching 20 m was recorded just below the main scarp. In the middle and lower part of landslide the 8m uplift is clearly visible together with concave depression reaching 22 m of depth. Within the landslide area, the cavity of the rock mass in the upper and middle parts is clearly indicated and it could be associated with the growth in high of colluvial masses (Fig. 2).

The shape of the landslide, known geological structure of the substrate and morphometry of shear plane, which was unveiled in the upper part of the landslide, gave rise to model the entire shear surface of the slide. Such a procedure allowed the calculation of the colluvium thickness (Fig.3) and its volume. Landslide reaches 42 m depth in the central part, and the volume of colluvium is approximately 4.2 million cubic meters.

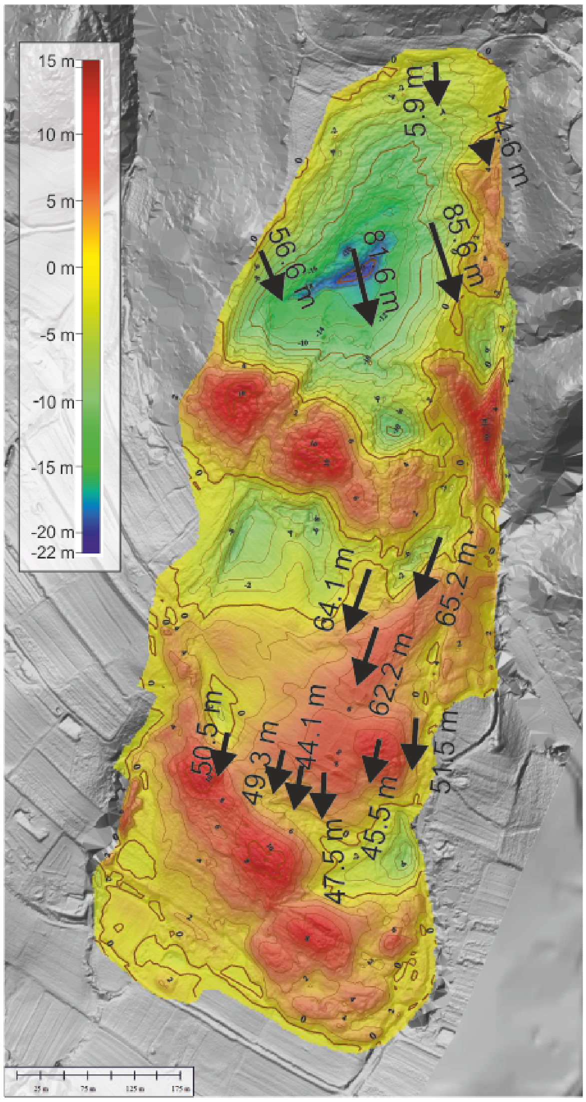

Fig. 2. Landslide deformation model calculated on the basis of photogrammetric data from 2009 year and airborne laser scanning data of July 2010; horizontal displacements based on a comparison of aerial photographs

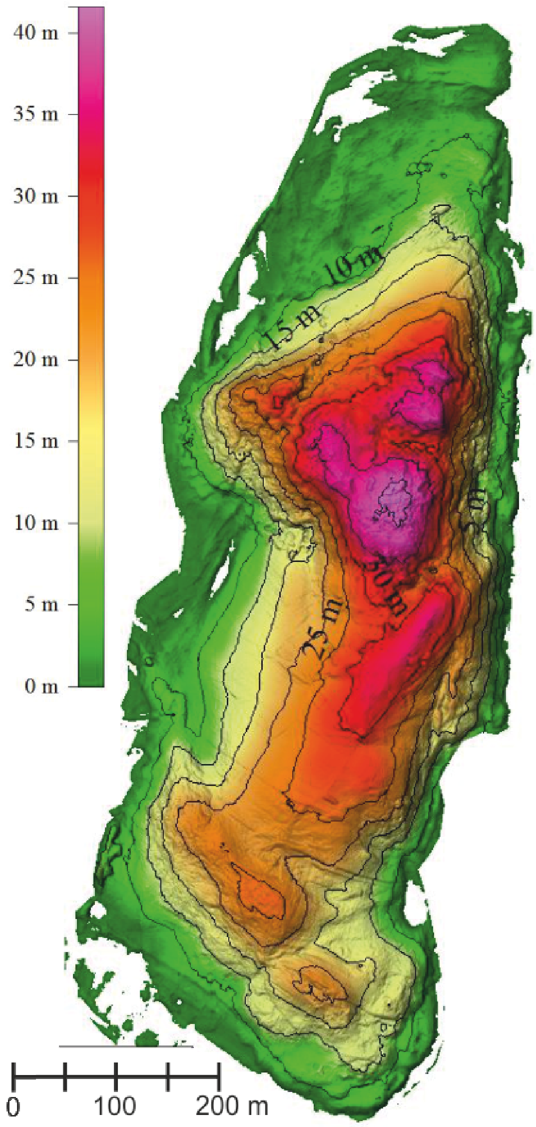

Fig. 3. The thickness of the landslide in Kłodne

The present activity of landslide

Within a year after catastrophic landslide decreased activity have been observed. Comparison of airborne and ground base LIDAR data showed that during the first year of the landslide zone below the main scarp has subsided by the next 2 m (Fig. 4). Within the area of colluvium, the increase of the surface by 4 m was observed. However, GNSS measurements made in 2012 and 2013 revealed no longer changes associated with the dynamics of landslide.

These observations were confirmed by the results of InSAR processing of TerraSAR-X data. Based on 20 scenes of StripMap mode SAR data a set of interferograms and PS points were generated using StaMPS MTI algorithm. The results represent a complete record of the dynamics of landslide between 6.10.2010 and 13.06.2012. For a number of the interferograms, a clear image of the phase differences for non-forested area of the landslide was obtained (Fig. 5). Their subsequent comparisons indicate a decrease in the activity of landslide in time. In the first period (between 10.06.2010 and 28.10.2010), the upper part of the landslide was subsided by about 25 mm. Between 28.10.2010 and 19.11.2010 the same area have decreased by another 15 mm. The obtained pattern of interferometric fringes was compared with numerical simulation of interferometric fringes calculated from vertical displacement map of the main event (Fig. 2). The both datasets, simulated and calculated from the data show that the interferometric deformation distribution is consistent with a model. It proves that the observed fringe is associated with the real deformation and not with other artifacts (e.g. atmosphere).

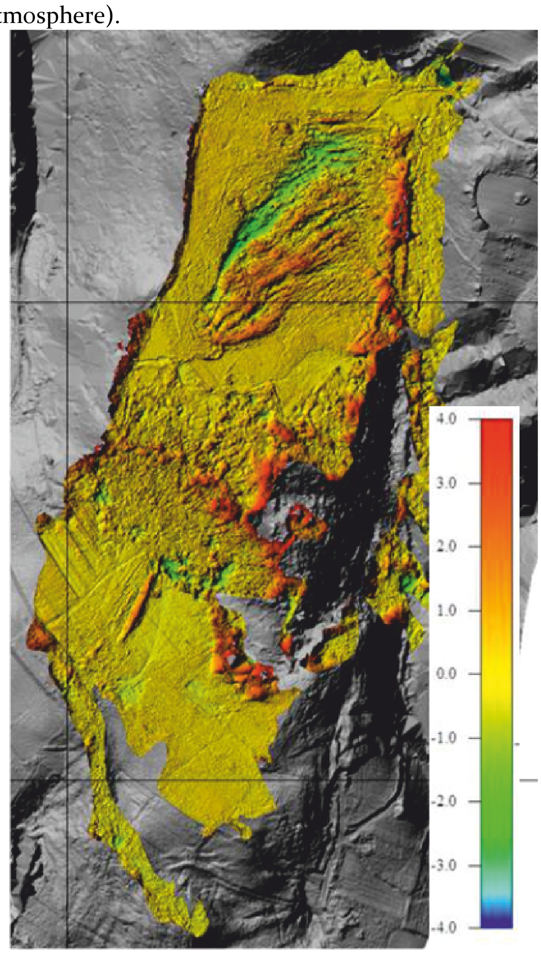

Fig. 4. The dynamics of landslides between July 2010 (measured with ALS) and May 2011 (measured with TLS).

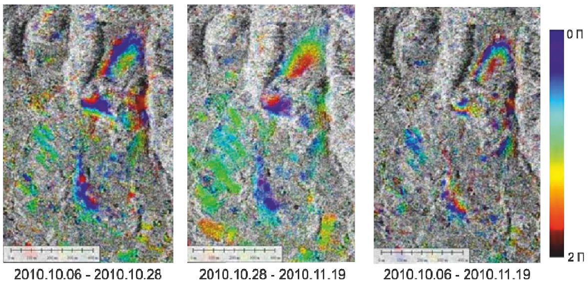

Fig. 5. Sample interferograms from satellite data acquired by TerraSAR-X

Conclusions

According to the archival data analysis (aerial photographs, interferometry with ERS-1/2 data) the landslide in Kłodne that was activated on 01.06.2010 is a new form. It was triggered be intense rainfall and favourable geological conditions. Landslide, whose volume is 4.2 million cubic meters, and the depth of colluvium reaches 42 m, showed the greatest activity in the first week of its duration. Through a comparative analysis of photogrammetric and laser data sets, the size of the horizontal and vertical displacements were estimated. Horizontal displacement reached 85.6 meters and is characterized by variability of sliding directions. Main deformation caused further depression reaching 22 m associated with increase of colluvial sediments accumulation reaching 8 meters. Monitoring of the Kłodne landslide activity with terrestrial laser scanning, SAR interferometry and GNSS showed that the growth rate gradually decreased over time. Landslide reached a relative equilibrium state after about a year after the main activity .

This study indicates that the synergic use of remote measurement methods creates opportunities for precise and relatively quick way to collect general information about landslide. Comparison of archival and recent data helps to reconstruct the state of the slope before the landslide, quantify the magnitude of deformation and monitor further landslide activity.

Acknowledgements

TerraSAR-X data for the research area were supported by research project number NN526146037 funded by Polish Ministry of Science and Higher Education.

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