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Landslide dynamics from high-resolution aerial photographs: A case study from the Western Carpathians, Slovakia

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ABSTRACT

The Ľubietová landslide is one of the largest landslide events in the Central Slovakia Neogene Volcanic Field area. Its present morphology resulted from several reactivation events. The latest one took place in 1977. We applied archive digital photogrammetry to build the historical topography of the landslide area and reconstructed its evolution from 1969 to 1998 at approximately decadal scale. Four sets of aerial photos of the area taken in 1969 (scale 1:16 000), 1977 (scale 1:14 000), 1988 (scale 1:17 000), and 1998 (scale 1:20 000) were processed using a digital photogrammetric workstation. Elevation data were extracted from all the photo sets. Then four high-resolution digital elevation models (DEMs) were generated and compared. Particular interest was placed on quantification of vertical ground displacements and volumetric mass redistribution. Both of them were calculated by subtracting two subsequent DEMs. Consequently, distribution and temporal variation of the landslide activity over three decades are outlined through differential raster images (differential DEMs) and cross-sections. According to our results, the 1977 reactivation event caused considerable vertical displacements up to ±5–7 m in the peak areas of depletion and accumulation zones. Accordingly, large volumes of material ($-148\,000$ m^3/$+84\,000$ m^3) were redistributed during this event. The dynamics of the 1977 reactivation event shows some specific features that are discussed within the broader context. Besides the new quantitative data, reconstruction of 3D topography of the site before and after the 1977 reactivation brought geomorphic evidence that the area was affected by more than one landslide event in the past.

1. Introduction

Landsliding is a natural geologic and geomorphic process that plays a key role in denudation, landform development, and Quaternary environmental changes in mountainous environments. Besides, landslides are major geological hazards that threaten human life and affect infrastructures and land use all over the world. Landslides represent very common geomorphologic forms in the Slovak Western Carpathians. Damages caused by slope movements exceed all others caused by geological hazard in Slovakia (Malgot and Baliak, 2001). Although most landslides occur in uninhabited areas, several large events and numerous smaller ones have reached marginal parts of towns or villages in recent history and repeatedly endanger these settlements. Some of them had a devastating effects and were named as "catastrophic" by Nemčok (1982). Two well-known large destructive reactivations in Slovakia, Handlová in 1960–1961 and Ľubietová in 1977, evolved in low relief areas after prolonged periods of heavy rainfall.

Understanding of the behaviour of landslides and identification of their possible triggering effects requires a good knowledge of the surface and subsurface kinematics of sliding masses. Consequently, deformation measurements are very important in landslide research. Geodetic techniques (tacheometric or modern GPS methods) are commonly used to access such information with sub-centimeter accuracy. These point-based measurements are time consuming if data density is high (spatially and/or temporally). However, 3D ground surface reconstructions, using Digital Elevation Models (DEMs), are a promising tool for morphological analysis of landslides and their source slopes. According to the scale, accuracy, and resolution needed, several techniques of remote sensing are available to create DEMs (for reviews see Mantovani et al., 1996; Metternicht et al., 2005). DEMs derived from aerial photographs have a resolution and accuracy mostly appropriate for modelling of landslides kinematics (from several centimeters to a few meters according to the scale of the photographs used). They are DEMs of the best quality together with LIDAR DEMs. Advantageously, the aerial photogrammetry can use archive materials (systematically collected in many countries over the

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past 50 years or so) and process them at relatively low cost. Aerial photogrammetry is, therefore, the only technique enabling accurate reconstruction of historic landslide dynamics (Hapke, 2005). Moreover, relationships among various landslide features, bedrock materials, landforms, and vegetation are more obvious through stereoscopic viewing than from a ground perspective.

In the case of historical image processing, the photogrammetric method known as archival photogrammetry is used to extract metric information from historical photos (Chandler and Cooper, 1988; Chandler et al., 2007). Recently, digital procedures have been developed, which automate the extraction of data from vertical aerial photographs. Due to their computation efficiency, DEMs are increasingly used in geomorphologic analysis to obtain quantitative data. Morphometric changes over several time intervals can be quantified by subtracting DEMs extracted for different dates of archive photographs. This technique has been successfully applied to detect changes in glaciated areas (e.g. Kääb, 2002), river bank erosion (e.g. Lane, 2000), coastal monitoring (e.g. Hapke and Richmond, 2000; Mills et al., 2005), gully erosion (e.g. Betts and De Rose, 1999; Betts et al., 2003), and landslide monitoring (e.g. Gentili et al., 2002; Casson et al., 2003; Mora et al., 2003; Pesci et al., 2004; Casson et al., 2005; Baldi et al., 2005, 2008; Brückl et al., 2006; Walstra et al., 2007; Dewitte et al., 2008). Differential DEMs and profiles can be used for such analysis.

Although the landslide research in Slovakia has a long-lasting tradition (e.g. Záruba and Mencl, 1969; Nemčok, 1982; Malgot and Baliak, 2000, 2001; Jelínek and Wagner, 2007), studies concerned with data indicating movement magnitude are only sporadic (e.g. Petro et al., 2004). To better understand the dynamics of reactivation events in the Western Carpathians, it is necessary to reconstruct past topographic changes from archival aerial photographs. This paper deals with the Ľubietová landslide, one of the most representative reactivations in the Slovak Carpathians (Nemčok, 1982). Its relatively large area (0.32 km^2), scarce woody vegetation, and the existence of the aerial photos taken repeatedly over the area make this landslide suitable for our study. Moreover, the site selected is of great public interest (due to endangering the inhabitants of Ľubietová village) and is included in the national monitoring programme sponsored by the Slovak Ministry of the Environment (SGIDS, 2009).

2. Regional setting

The Western Carpathians form the northernmost part of the European Alpides, linked to the Eastern Alps in the west and the Eastern Carpathians in the east (Fig. 1A). The alpine folding and overthrusting resulted in the complex north-vergent nappe structure of the Western Carpathians formed during the Cretaceous up to the Miocene (Plašienka et al., 1997). Based on their geodynamic development, the Western Carpathians are traditionally divided into externides and internides mutually separated by the complicated tectonic suture of the Pieniny Klippen Belt (Kováč et al., 1997). The externides are formed by a huge complex of neo-Alpine (i.e. Cenozoic) flysch nappes (accretionary complex) thrust over the foredeep that covers the flanks of the North European Platform. The internides encompass several palaeo- and meso-Alpine crustal nappe stacks consisting of Early Palaeozoic (Hercynian) basement and Late Palaeozoic and Mesozoic sedimentary cover and nappe complexes. They are overlain by post-nappe Late Cretaceous to Neogene sedimentary and volcanic formations. Recently, a great part of the internides forms a wide belt of highlands (Core Mountains) separated by valleys and intra-mountain basins which set the typical pattern of the Western Carpathians' scenery.

Landsliding is a very common geomorphologic process as well as the most dangerous geodynamic phenomenon in the Western Carpathians (Malgot and Baliak, 2001). According to Liščák and Caudt (1997), over 15 000 landslides (covering almost 4% of the total area of Slovakia) have been registered in the Slovak part of the Western Carpathians. Their distribution is linked primarily with geologic structure (e.g. Nemčok, 1982; Maas et al., 2005) and they frequently initiate on surprisingly gentle slopes (<7°). The most affected areas are composed of Cenozoic flysch and volcanic rock mass, where landslides represent almost 15% of the total area (Nemčok, 1982). The recent landslides developed on the upper parts of older ones which originated predominantly during the most humid periods of the Holocene (Margielewski and Urban, 2003; Margielewski, 2006; Hradecký et al., 2007, Pánek et al., 2009, Klimeš et al., 2009). Although all these studies deal with the Outer Western Carpathians, similar conditions may be assumed for other Western Carpathian areas.

The Central Slovakia Neogene Volcanic Field area is a part of a larger volcanic area in the inner side of the Western Carpathians. Various types of effusives, pyroclastics, and tuffites originated mainly during Middle to Late Miocene volcanic activity overlay older formations of Palaeozoic to Early Neogene age. The young and strongly structured relief of the neovolcanic area was formed by intensive erosion and differential tectonic movement (Ondrášik, 2002). The high density of slope deformations in this area is conditioned primarily by conspicuous differences in strength characteristics of two overlain rock complexes — lower Palaeogene or Neogene clay-rich sedimentary layers (soft, weak, and impermeable) and upper epiclastic volcanic rocks (hard, rigid, and permeable). The most favourable conditions for slope failure arise when contacts of both complexes are exposed due to erosion (Nemčok, 1982).

The study site is located near Ľubietová village (central Slovakia) at the northern promontory of the Poľana stratovolcano (Fig. 1C) which is part of the Central Slovakia Volcanic Field (Fig. 1B). The geological setting of the surrounding area is more complex, because denudation remnants of Cenozoic sedimentary and volcanic rocks rest on the overthrust contact of two palaeo-Alpine crustal units, the Vepor and the Fatra–Tatra belt. This contact zone is characterized by complex lithology and strong tectonic reworking (e.g. Plašienka, 1997).

The catastrophic Ľubietová landslide is a part of the wide sliding area situated on the left side of the Hutná stream (Fig. 1D). The area is built up of Cenozoic rocks. Rigid complexes of volcanic rocks (epiclastic volcanic breccias to conglomerates predominantly of andesitic composition) and polymictic gravels to conglomerates (Kordiky formations) constitute the uppermost parts of slopes (Fig. 1D). Their marginal parts are disintegrated into variously oriented blocks, displaced from the main rock mass. Slow sinking and rotation of these blocks disturb the stability of the slope. Moreover, both rigid rock types are permeable and steadily supply water to the slope. In contrast, underlying Neogene and Palaeogene clay-rich layers are weak and impermeable. As a consequence the stability of slopes is frequently near its limit value despite their gentle inclination (6°–7° on average). Landslides, mainly translational, occur on lower parts of the slopes covered by thick (up to 30 m) Quarternary colluvial deposits. All processes were described in detail by Nemčok (1982).

The investigated landslide is situated on an eastward dipping slope (Fig. 2A). It is an 8–25 m thick, translational slide that ranges from ~610 to ~440 m a.s.l. The three-lobed head part of the landslide body joins downslope into the main flow. The maximal length (measured across the longest central flow) is over 1 200 m, and the maximal width of the landslide is about 500 m (Fig. 2B). It affects an area of approximately 320 000 m^2 with an average slope gradient of 6°–7°. The total volume of the displaced mass was estimated to be about 4×10^6 m^3 (Fussgänger et al., 1978; Nemčok, 1982). The landslide reactivation in 1977 was triggered by a prolonged period of rainfall and accompanying snowmelt. From the beginning of December 1976 to the end of February 1977 the total amount of precipitation was about 190% of the long-term 1931–1975 average (calculated using data from the rain-gauging station in Ľubietová located near (~150 m) the study site). After the movement initiation, the landslide