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Report on a recent deep-seated landslide at Gírová Mt., Czech Republic, triggered by a heavy rainfall: The Gírová Mt., Outer West Carpathians; Czech Republic

Abstract A large deep-seated landslide, triggered by a heavy rainfall, activated early in the morning on May 19, 2010 along the SW slope of Gírová Mt., NE Czech Republic. The landslide occurred within a zone of pre-existing deep-seated gravitational deformation, and it was accompanied with pronounced ground liquefying in the central and lower portion of the sliding mass. The precipitation that triggered the landslide was about 244.6mm that fell between May 15th and 18th with an average of 61mm/day. No properties or lives were lost. However, the landslide provided a good case study on triggering factors and process of liquefaction at mountain slopes in the E Czech Republic and adjacent areas.

Keywords Landslide · Liquefaction · Deep-seated gravitational deformation · Outer West Carpathians

Introduction

A large and deep-seated landslide, triggered by a heavy rainfall, activated on May 19, 2010 along the SW slope of Gírová Mt., NE Czech Republic (WGS: 49°31′51.692″ N, 18°47′30.43″ E, Fig. 1). This rainfall event resulted in disastrous floods and landslide activities along the West Carpathians Mts. and Central Europe. A total of 189 active landslides were registered in the area of eastern Czech Republic (Source: Czech Geological Survey) and 551 in the area of eastern Slovakia (Liščák et al. 2010). The most severe damage occurred in southern Poland, where a total of 1,345 landslides activated. Consequently 1,709 houses were damaged and 560 completely destroyed with a total loss of about 2.9 Billion Euro on buildings, infrastructure, etc. (Forowicz 2010; Ministerstwo Środowiska 2010).

The Gírová landslide is regionally outstanding for its dimensions, mechanism, and well-developed landslide morphology. It occurred within zone of pre-existing deep-seated gravitational deformation (DSGD), and it was accompanied with pronounced liquefying of the sliding mass (i.e., a phenomenon the unconsolidated materials transform into a substance behaving like a liquid due to complete saturation). The landslide provided a good case study on triggering factors and process of liquefaction on mountain slopes in the E Czech Republic and adjacent areas.

Methods

Immediately after its failure, the landslide was surveyed, consisted of field mapping, ultralight-plane survey by pilot J. Prchal (CIS AIR Int. Slušovice), analyses of orthophotos taken 2004 (source: http://geoportal.cenia.cz/), a digital elevation model (DEM) at a 1:10,000 scale (source of data: ZABAGED), structural measurement, analyses of a 1:50,000 geological map (source: Czech Geological Survey), and radiocarbon dating of a buried wood sample in the laboratory in Kyiv, Ukraine by Dr. Skripkin. The airborne quasi vertical images were rectified onto an orthophoto in the computer program ArcGIS for reconstructing the kinematic process.

Landslide structure, geological settings, kinematics, and history

The landslide started to move early in the morning on May 19, 2010 (Paštiková 2010) at the SW slopes of the Gírová Mt. in the easternmost part of the Czech Republic (Fig. 1a). The movement came to a complete stop several days after the initial movement. The failed sliding mass had an elongated and curved shape along the original valley (Fig. 1b) with a total horizontal length of 1,130 m and a straight horizontal length of 1,060 m. The maximum width of the main landslide is about 200 m. However, together with the subsequent sliding and sagging of the crown, it became about 300 m wide. The estimated maximum depth is about 30 m in the upper part and about 10 m in the toe area. The entire landslide consisted of two distinct parts: (1) the landslide itself in the upper part with features typical for any rotational deep-seated landslides such as head scarp, slightly back-tilted landslide blocks, and sagged crown due to unloading (Fig. 2a and b) and (2) earthflow part in the lower two thirds of the slope failure (Figs. 2c–f and 3). The estimated volume of the entire sliding mass is about 2.8 million cubic meters with a volume of 2,073,451 m^3 in the upper part and 735,750 m^3 in the earthflow part, respectively.

The upper part is evidently structurally predisposed with other important contributing factors such as the original topography, specific and generally incompetent lithology of the flysch rocks and existence of a fault and a historical DSGD, and thus relatively deep weathering of the host rock. It has developed in the flysch rock composed of rather thin bedded alternating clay stone, shale and sandstone of the Raztoka Member of the Soláň Formation (Upper Cretaceous–Paleocene) of the Rača Unit of Magura Nappe, Outer West Carpathians (Fig. 1a). The bedding is monoclinal in the area of the head scarp (Fig. 4a and c). The Raztoka Member is overlain by the Lukov Member, which is composed mostly of several meters thick sandstone beds and is cracked at several places due to the unloading. At some locations along the NE and NW slopes of the Gírová Mt., pseudokarst caves developed (Pavlica 1979). The host rock of the landslide was partly formed also by quaternary slope sediments (Fig. 1a). The DSGD contains up to 25 m high scarps, flats, and swamps. It is about 500 m wide and about 1,400 m long. The scarps of the DSGD developed along mass movement normal faults, e.g., along a documented fault 179/76° with drugged fold, mylonitized clay fill, and slip about 35 cm (Fig. 4c and e).

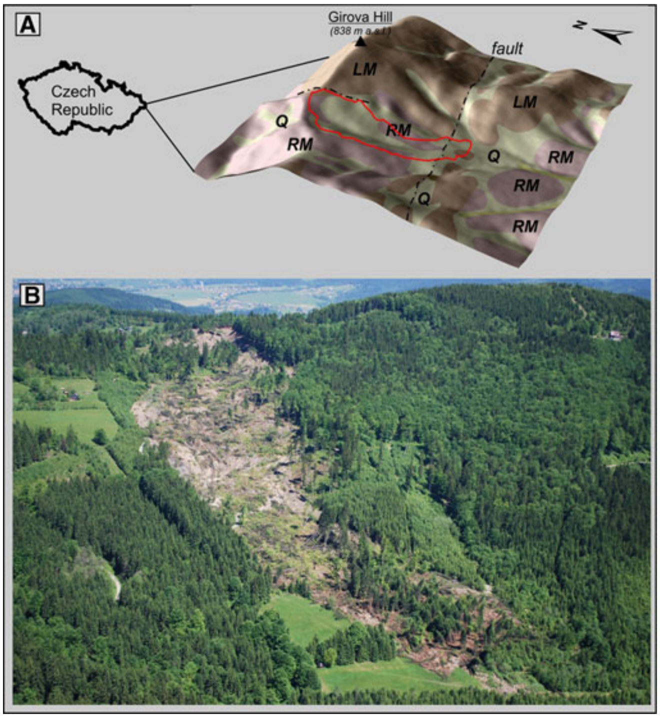


Fig. 1 General setting of the Gírová landslide area: **a** 3D Visualization of the geological map from SW. *Q* quaternary slope deposit, *RM* Raztoka Member, *LM* Lukov Member (Source of data: ZABAGED and Czech Geological Survey); **b** oblique aerial photo of the Gírová landslide from S (Photo by I. Baroň; June 5, 2010)

The head scarp is asymmetric and wedge-shaped (Fig. 2a). It consists of a linear wall up to 20 m high and 260 m long in the east with a dip of 264°/34° (Fig. 4a). This part of the head scarp probably developed following a fault plane (Fig. 1a). The major E–W striking tectonic jointing facilitated the rock separation (Fig. 4b). The bedding is sub-horizontal and perpendicular to the head scarp (Fig. 4c). The surface of the scarp wall was scratched by landslide striations. The striations indicated the displacement vector and their dip azimuth varied from 190° to 200° (Fig. 4d).

The lower part, which was actually a subsequent earthflow, occupied the lower two thirds of the entire landslide. It started in a place of about 15 m high scarp situated where the slip surface of the upper part of the landslide outcrops (Fig. 3). A mass consisting of older landslide deposit, debris, and organic-rich sediments in the original valley was completely saturated by water. Additional earthflows, mud lakes, swamps, landslide ponds, small transversal ridges, flank ridges, etc. represent the typical morphology of the earthflow. Buried tree trunks and branches were exposed from former landslide-related deposits in the lower part. The toe is up to 3 m elevated over the stable ground in the lowermost part (Fig. 2e and f), and it caused a progressive failure before the toe. Abandoned artesian springs with sediment ring around as well as the active ones (2 weeks after the triggering) occur in still stable ground around the toe (Fig. 2g). The artesian springs indicated a high groundwater pressure.

Kinematic reconstruction of the horizontal displacement was done by comparing the orthophoto before the event (2004) and rectified vertical aerial photo taken during the ultralight-plane survey shortly after the landslide event (June 5th, 2010, Fig. 5). The results suggest that the upper block moved about 85 m towards the SSW followed up by a 22-m subsequent sliding of the head (horizontal component of movement only). The largest displacement occurred in the upper area of the earthflow near the western flank with a horizontal distance of about 253 m. In contrast to the western flank, the largest horizontal movement was about 133 m in the eastern flank. The estimated displacement decreased to 75 m in the toe area (Fig. 5).

A wood piece, which was buried by an older mass movement, was taken from the accumulation flank in the SW part of the active landslide and it was dated by conventional radiocarbon method. The results of radiocarbon dating indicated that one prior event was occurred about 5910±120 ^{14}C years BP (sample Ki–16615) ago. For a more comprehensive information on the past mass-movement periodicity here, however, a systematic research on buried organic pieces would be required.

Fortunately, the landslide did not cause any remarkable damage to population or infrastructure. Only forest and local roads were cut as well as the local water and power supply lines. The most severe damage was, thus, on the forest property.

Triggering factors

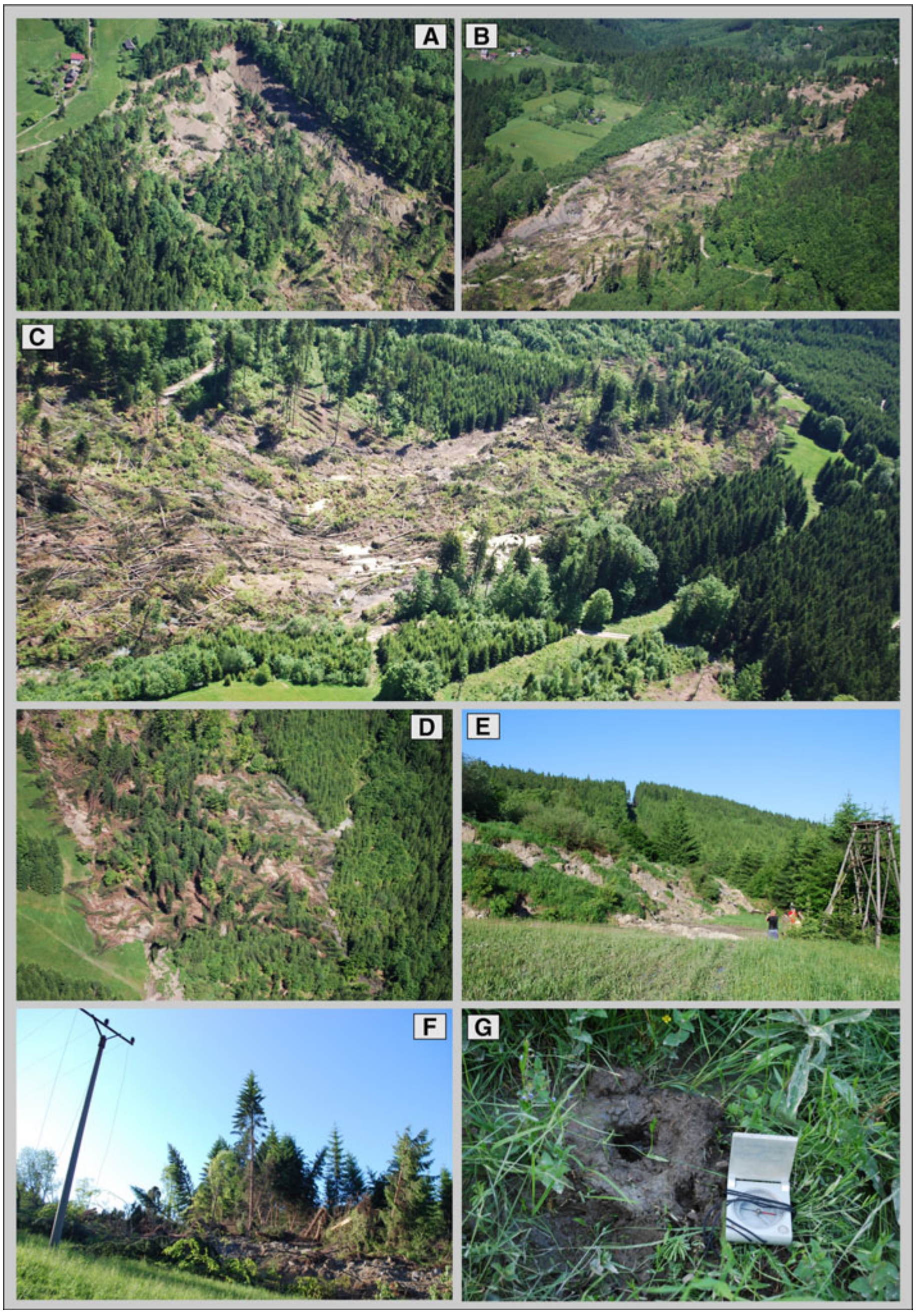
The immediate triggering factor of the mass movement at Gírová Mt. was the saturation of the substrate due to excessive rainfall in the middle of May 2010, which was anticipated by other heavy rains and the ground oversaturation in the early May. A large cyclone over the Central Mediterranean, which moved along the track “Vb” (after van Bebber) over the Balkan Peninsula towards the NE, was the main synoptic factor of that major rainfall event in the Beskydy Mts. in the middle of May. The rain started in the evening of May 15th, with only 20–35 mm of precipitation per 24 h. Later on, during May 16th and May 17th, the rainfall intensity reached up to 8–15 mm/1 h in the mountain areas. The wind effect on the windward slopes raised the total precipitation up to 80–115 mm in 24 h. Heavy rainfall continued also into May 18th and decreased only on May 19th. This rainfall subsequently caused a double-peak flood in NE Czech Republic, the highest in the period of recording on the Olše River (since 1925). The overview of the precipitation distribution and summary for selected meteorological stations near the landslide site are presented in Fig. 6 and Table 1. Also, the flood record at selected rivers is shown in Fig. 7.

There are no meteorological stations within the landslide area. However, the nearest one located in Jablunkov about 5 km away recorded a total precipitation of about 244.6 mm between May 15th and 18th (Table 1), just a few hours before the landslide triggering. The triggering of the landslide was attributed to such an intense precipitation within a short time period.

Discussion and conclusions

Although it was just one of more than 2,000 of landslides triggered by the 2010 May rainfall event in S Poland, Czech

Fig. 2 Photos of the Gírová landslide: **a** oblique aerial photo of the head scarp from SW, **b** oblique aerial photo of the upper body from SE, **c** oblique aerial photo of the lower part with a 15-m-high scarp and distinct liquefaction of the mass, **d** quasi normal aerial photo of the toe, **e**–**f** toe of the landslide and **g** sedimentary ring along an abandoned artesian spring below the landslide toe (All photos by I. Baroň; June 5th, 2010)



Republic, and Slovakia, the landslide complex at the Gírová Mt. is regionally outstanding for its dimensions, mechanism, and well-developed landslide morphology. It provided a nice case study of landslide on the timing of triggering and on the process of liquefaction of mountain slopes in the E Czech Republic and adjacent areas.

Unfortunately no in situ measurements of ground water levels and pore-water pressure were available within the landslide mass before or during the event. However, the triggering of the landslide by water saturation of the host rock due to heavy rainfall is obvious. As many other deep-seated landslides in the area of the Flysch Carpathians Mts. (e.g. in 1997; Krejčí et al. 2002) the Gírová landslide was also triggered with a certain delay after the flood peak. In this case, it was about 24 h after the second culmination peak of the Olše River in Český Těšín.

This case study reaffirms a fact that large active landslides usually develop within existing unstable areas of older and dormant deep-seated landslides or deep-seated gravitational deformations (see Krejčí et al. 2002; Baroň et al. 2004; Klimeš et al. 2009). The study also showed that the mass movement could be repeatedly activated in this area here similarly to other Carpathian deep-seated landslides presented by Baroň et al. (2004) or Klimeš et al. (2009). Although the event frequency

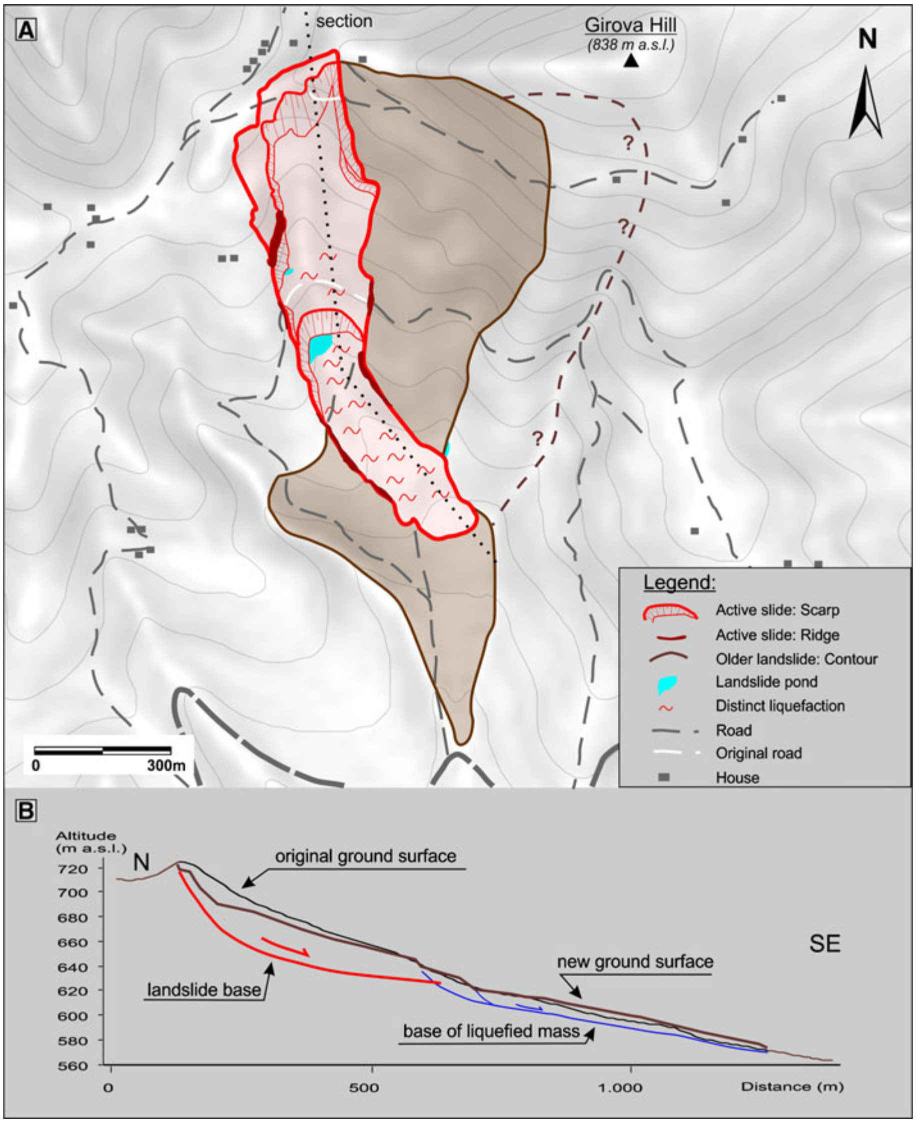


Fig. 3 Geomorphic map **a** of the landslide at Gírová Mt. obtained from the field survey, ultralight-plane survey and orthophotos, superimposed on the slope-gradient map with steeper slopes in *darker gray*; **b** hypothetical section of the landslide (Source of DEM: ZABAGED)

was not well studied in detail at the Gírová site due to the limited time and budget, geomorphic mapping proved several older landslide accumulations in the site and at least one activity phase was proven by radiocarbon dating about 5910±120 ^{14}C years BP.

On the other hand, the liquefying of the substrate and the development of rather shallow earthflows and secondary landslides at the frontal parts of deep-seated rotational slope failures in the Flysch Belt of Outer West Carpathians, similar to the this reported example, was also noted by Baroň et al. (2004) or Klimeš et al. (2009). They observed that such shallow landslides and earthflows are usually much more rapid and destructive than deep-seated precursors. However, the factors of liquefaction at the mountain slopes still remain a subject of further discussion. The effects of landslide geometry and kinematic deformation on the generation of excess pore pressure and the possible liquefaction of sliding blocks were studied by van Asch et al. (2006). They proposed a simple analytical model of landslide liquefaction based on classic soil mechanics theory. The differential movements of rotational slides result in differential strains which are transferred to excess pore pressures. For landslides characterized by curved slip surfaces, the lower parts are subject to compaction and an increase in pore pressures during a movement (van Asch et al. 2006). We also speculated that the role of outcropping slip surface of the precursory rotational slide plays an important role in the liquefying of the mass due to sudden differential unloading of the mass (in the case, when the rotational sliding plane outcrops higher at slope). This question is, however, a subject of future research.

The investigation of Gírová landslide could also contribute to a discussion on the critical value of precipitation and thus water saturation, which could trigger a deep-seated landslide. Back numerical analysis of deep-seated landslides in the Rača Unit of the Flysch Belt of Outer West Carpathians proved that such landslides could be triggered by high pore-water pressure due to ground-water table close to the ground surface as a result of extreme rainfalls (Baroň et al. 2005). Although any

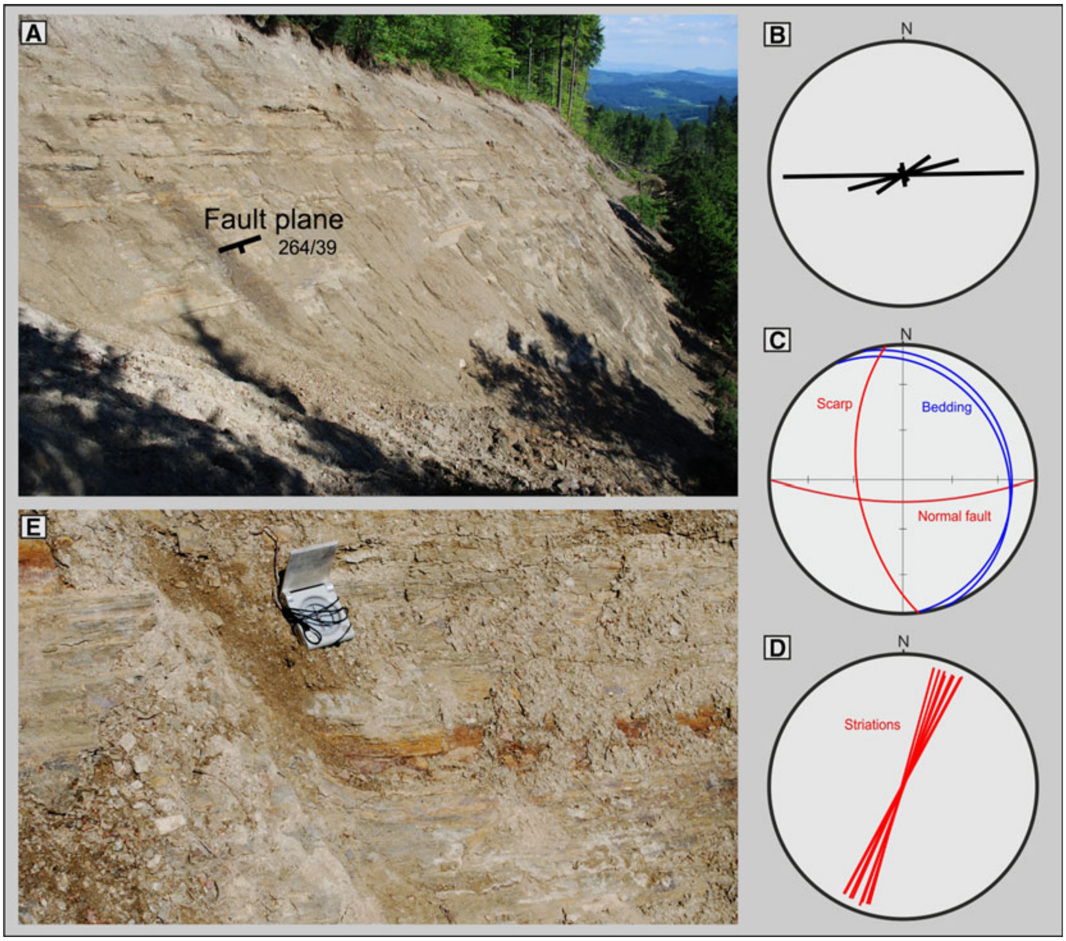


Fig. 4 Structural setting of the Gírová landslide: **a** photo of the head scarp, which developed probably along a fault plane, **b** rose diagram of measured joints, **c** the bedding, the head scarp, and a DSGD-related normal fault performed in the lower hemisphere of the Lamberdt projection **d** diagram of approximate orientation of mass-movement striations at the head scarp surface and **e** photo of the DSGD related normal fault with a dragged fold (Photo by I. Baroň; June 5, 2010)

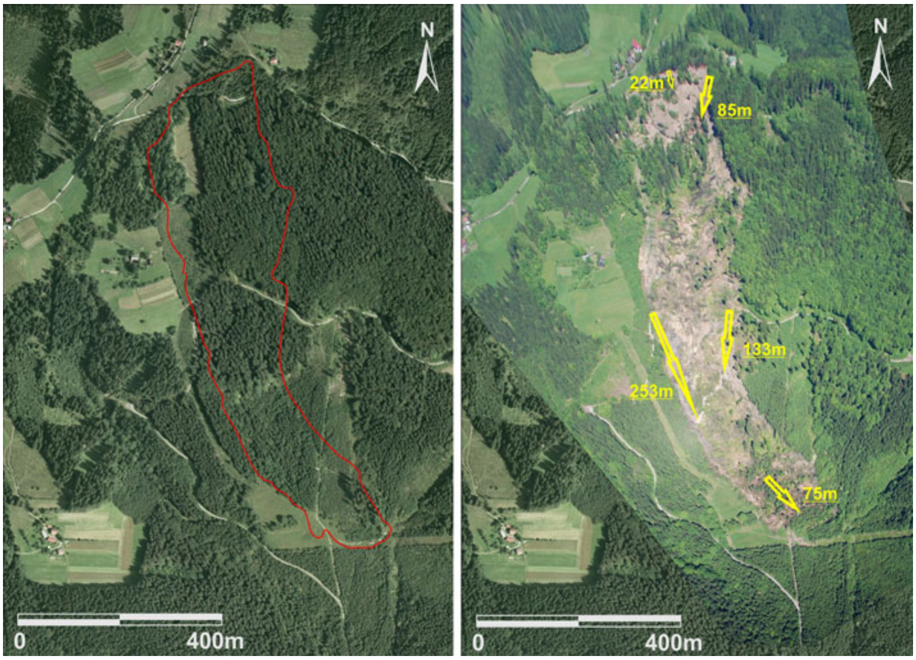


Fig. 5 Kinematic reconstruction of displacement by comparing the orthophoto from 2004 (*left*) and pseudo-orthorectified aerial photo (*right*) taken during the ultralight-plane survey shortly after the landslide event on June 5th, 2010. The *numbers* refer to the horizontal displacement value, the *arrows* indicate the general displacement vector (Source of orthophoto: http://geoportal.cenia.cz/, rectified airborne photo by I. Baroň)

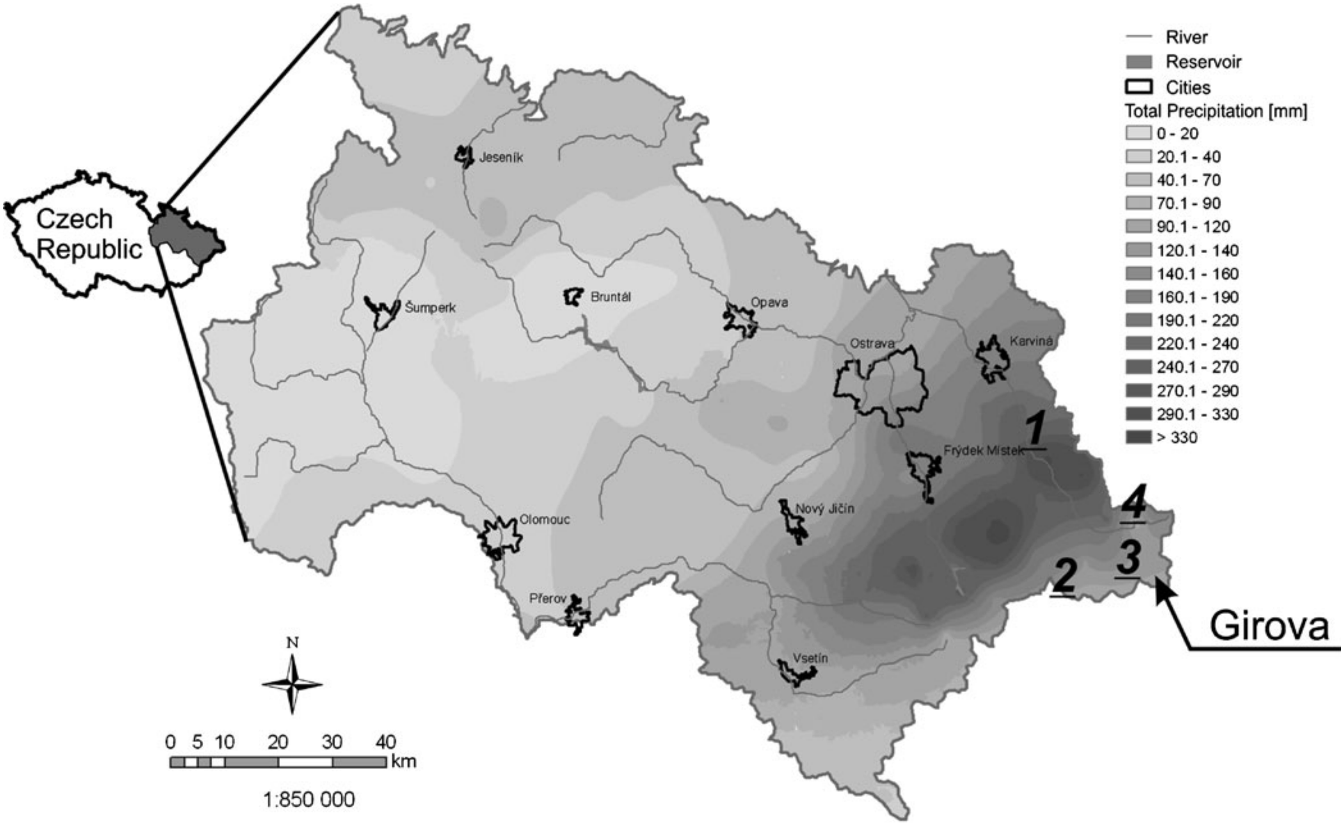


Fig. 6 Map of total precipitation in NE Czech Republic from May 15 to May 18, 2010. Meteorological stations are numbered: *1* Český Těšín, *2* Horní Lomná, *3* Jablunkov, *4* Nýdek (source: Czech Hydrometeorological Institute)

exact record on precipitation at the landslide site before its triggering did not exist, we can speculate that it should be very similar to the nearest meteorological station in Jablunkov, which is about 6 km away. The total precipitation there reached about 244.6 mm between May 15th and 18th, just a few hours before the landslide triggering. This amount of rainfall, connected with previous substrate saturation, was critical. This was, of course, dependent on many passive and site-specific factors. However, recognizing such a critical amount of precipitation is needed for any alert in the early warning process in regional scale. The best-documented historical landslide event in the Czech Republic (July 1997, E Czech Republic) was triggered by an average precipitation of 257 mm (Kirchner 2001) within a time period of 5 days. During this landslide event, more than 1,500 landslides of different types (e.g., soil slips, flows, and rotational and translational landslides) originated causing extensive damage to buildings and infrastructure (Krejčí et al. 2002). Bíl and Müller (2008) presented a threshold value for shallow landslides about 100 mm for shallow landslide event in E Czech Republic in 2006, which is two to three times lower than that given by Gil (1997) for the Polish Carpathians where landslides occur with a rainfall of 200–300 mm within 20–40 days. In both cases, however, the results are consistent in terms of the daily average value of total cumulative precipitation (TCP) triggering the landslide, i.e.: about 10 mm day^{-1} (Bíl and Müller 2008). The daily average value of TCP observed in this case study was six time higher than their observations.

Table 1 Total daily precipitation registered in selected meteorological stations

Meteorological station	Total daily precipitation [mm]				Total precipitation in May 15–18, 2010 [mm]
	May 15	May 16	May 17	May 18	
Český Těšín	17.6	120.9	74.4	39.2	252.1
Horní Lomná	10.5	104.0	50.4	30.0	194.9
Jablunkov	12.4	115.1	75.3	41.8	244.6
Nýdek	24.0	146.0	96.5	71.0	337.5

For their location, see Fig. 6 (source: Czech Hydrometeorological Institute)

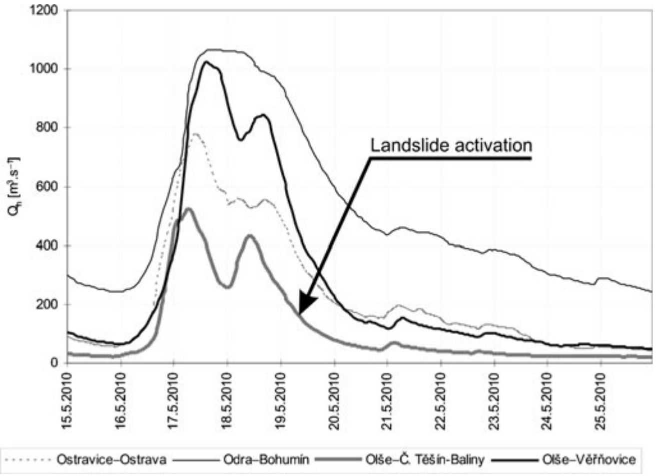


Fig. 7 Flood record on different rivers of NE Czech Republic. The landslide activated within a 1-day delay after the second flood culmination peak of the Olše River at the nearest recording station in Český Těšín (source of data: Czech Hydrometeorological Institute)

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