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Identification of *flysch* landslide triggers using conventional and 'nearly real-time' monitoring methods – An example from the Carpathian Mountains, Poland

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A B S T R A C T

This paper presents a study of active landslides in the Carpathian *flysch* in Poland. Site investigation of 15 landslides was conducted during the reconstruction of the Szymbark - Szalowa road. The landslides selected for analysis are located in slopes with inclination from 9° to 18° of the Oligocene age characterized by shallow groundwater levels. These slopes are made of soft clays and claystones, interbedded by sandstones that allow seepage processes. The *flysch* mixtures of: weak soils and stiff rocks typically pose some difficulties for in-situ and laboratory tests. Therefore, methods for the recognition of landslide size, depth and activity need to be applied. Site investigations and laboratory tests started in 2006 with conventional inclinometer and piezometer monitoring measurements. However, significant time-lags between the measurements made it difficult to quantify landslide triggers. Therefore, a more comprehensive, 'nearly real-time' landslide monitoring network was deployed on May 2010, the first of this type in Poland. This system consisted of a weather station and three monitoring field stations with continuous recording of 3D inclinometers, in-place tilt sensors and pore-pressure transducers. At depths of 11–15 m, the online measured displacement reached 33–500 mm. Heavy rainfalls, and water infiltration led to pore-pressure changes ranging from 50 to 100 kPa. In June 2010, an acceleration of ground movements occurred after the highest monthly rainfall of 225–303 mm during a major flood in southern Poland and again in July 2011. Slope saturation was found to be the primary cause of landslide activation, and groundwater pore-pressure variations of 100% were found critical, as a trigger for landslide accelerations in the Polish Carpathian *flysch*. The appearance of high pore-pressures variations could be used as an initial warning signal before the significant movements.

1. Introduction

The identification of landslide hazards is a very important but difficult task. According to the Polish Geological Survey (PGI), the 60,000 mass movements in the Polish Carpathians constitute over 95% of those in Poland (Chowaniec et al., 2015). Every year, landslides are activated or reactivated by intense precipitations causing significant economic losses. Mapping of landslides at the scale of 1: 10000 and free access to the SOPO - Polish National Landslide Counteraction Project Database (Grabowski et al., 2008) gave the possibility to characterize these landslides in terms of shape, size and approximate depth at a regional scale. However, accurate detection of slip surfaces depths, movements, their directions and fluctuations of groundwater conditions is required for landslide risk management on a local scale. Different types of monitoring systems such as: inclinometers, extensometers, piezometers and pore-pressure transducers, assist in predicting landslide triggers. In particular, conventional inclinometers can detect depth and direction of ground movement along the sliding surfaces and validate the results of previous geological exploration. This became a standard in the world over 60 years ago (Dunnicliff, 1993). However, inclinometer equipment has been in use in Poland for 40 years and the identification of *flysch* landslide activity using this method was limited (Nescieruk and Raczkowski, 2012; Zabuski, 2013). A standard landslide investigation in Poland is usually performed using core drillings, laboratory tests and geomorphology studies. Several attempts to identify landslide triggers using correlation of rainfall intensity and displacement were made in Poland (Gil, 1997; Starkel, 1997, 2011; Raczkowski and Mrozek, 2002; Gil and Dlugosz, 2006) and other countries (Vaughan and Walbanncke, 1983; Hutchinson, 1988; Senneset, 1998; Au, 1998; Corominas and Moya, 1999; Van Asch et al., 1999; Angeli et al., 2000; Aylsworth et al., 2000; Iverson, 2000; Larsen, 2002; Baum et al., 2003; Winter et al., 2010; Jovancevic et al., 2015; Marjanovic et al., 2018). Some of the

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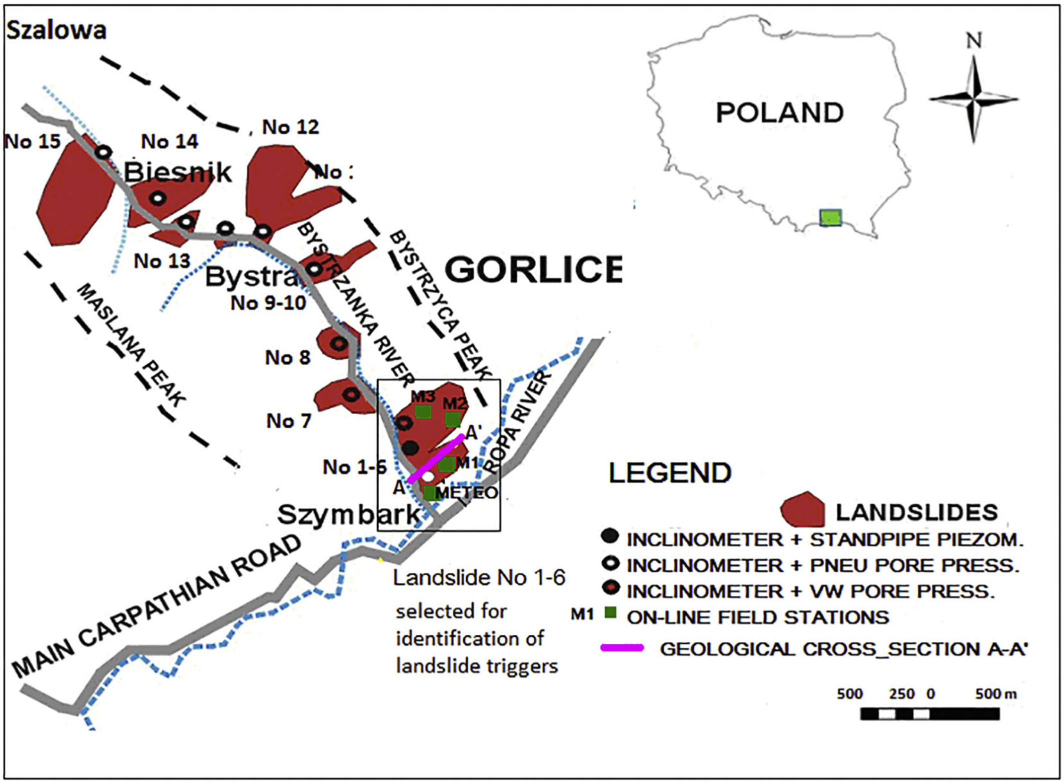

Fig. 1. Localizations of landslide monitoring network at Szymbark-Szalowa road.

analysts studied *flysch* soil's strength parameters using back analysis (Berti et al., 2017) or ring-shear apparatus tests (Van Asch et al., 2007). Fluctuations of pore-pressure at sliding depth were recognized in other publications as a very important indicator of sliding activity (Skempton, 1964; Tofani, 2000; Sarsby, 2000; Crosta and Frattini, 2003; Cornforth, 2005; Hungr et al., 2005; Matsuura et al., 2008; Cano and Tomás, 2013). A different approach for slope failure prediction is the use of semi-empirical methods based on deformation time history (Saito, 1965; Varnes, 1978; Voight, 1989; Federico et al., 2012). Most of these landslide triggers identification approaches are based on surface displacements induced by rain. However, using surface displacements for deep-seated Carpathian landslides has some limitations. Continuous inclinometer measurements of ground displacements inside the slope could be more efficient in such landslides. Real-time or 'nearly real-time' in situ instruments with many different multiple sensors which can provide accurate meteorological, ground displacements and groundwater levels data are available. These measurements could be processed and interpreted in early warning systems (EWS) to safeguard the people and important infrastructure (Intrieri et al., 2012).

In this paper, conventional and 'nearly real-time' monitoring methods and relevant results are described. The first attempt of the usage of on-line 'nearly real-time' landslide monitoring measurements for the identification of landslide activation in Polish Carpathians is presented as an example. Practical application of the measurements at selected *flysch* slopes, advantages and limitations of the chosen methods are described in detail. These include identification of geological engineering conditions, sliding surface depths, determination of movement ranges and landslide triggers. This enabled a detailed engineering geological model to be derived for numerical modelling (Bednarczyk, 2008a, 2012). Topics connected with the relations between rainfall, pore-pressure in the ground and variations of groundwater levels causing landslide activation were investigated. The conventional monitoring measurements started in winter 2006 and until 2013 were performed every 1–2 months and then every 3–6 months until the end of 2015. The results of these measurements were delivered to the Local Road Authority for remediation works. The first in Poland on-line landslide monitoring system was installed in May 2010 with the aim of delivering data for the interpretation of landslide triggers. Another objective of this work is to also assess the efficacy of remediation works. Partial stabilization by anchors, high tensile Geobrugg meshes, internal and surface drainage together with gabion walls was realized in 2009. However, some of these works were not fully effective during heavy rainfalls of over 460 mm in May–June 2010.

2. Site localization and characterization

2.1. Engineering geology and geomorphology

The study area is located in the Bystrzanka River Valley near the city of Gorlice (SE Poland). Along the Szymbark-Szalowa public road which has a length of 10 km, with 30% of the area affected by 15 landslides (No 1–15 in Fig. 1). The analyses presented in this paper are focused on six landslides (No 1–6) located in the lowest part of the valley (Figs. 1 to 4). These pose a serious threat to the public road connecting four villages. Landslides have areas ranging from 0.37 to 0.6 km^2. The study area is situated in the marginal part of the Magura Nappe, which slid over the central Carpathian depression unit. Parallel folds, north of the river of Ropa are cut by the multiple faults into blocks and refolded. The majority of the Bystrzanka River Valley is occupied by Eocene rocks of the Magura Nappe (Kijowska-Strugala, 2015). The area investigated is situated between two main geomorphologic units of Beskidy Mountains (Beskid Niski Mts.) and Carpathian Foreland (Gorlickie Foothills - Luzna Valley). Massif of Beskid Niski is transverse to the main Carpathians ridge. It is built of relatively low hills ranging of 400–850 m a.s.l. The surrounding hills rising up to a height of 350 m above the valley floor. The *flysch* bedrock is composed of low strength claystones and sandstones resistant to weathering processes. More resistant Magura sandstones observed on the main ridges of the Beskid Niski Mts., constitute about 30% of the area. *Flysch* units were folded and cut by faults, elevated and displaced approximately