Geomorphology 274 (2016) 193–209

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Combining geomorphological mapping and near surface geophysics (GPR and ERT) to study piping systems

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ARTICLE INFO

Article history:
Received 12 April 2016
Received in revised form 6 September 2016
Accepted 7 September 2016
Available online 9 September 2016

Keywords:
Tunnel erosion
Ground penetrating radar
Electrical resistivity tomography
Carpathians

ABSTRACT

This paper aims to provide a more comprehensive characterization of piping systems in mountainous areas under a temperate climate using geomorphological mapping and geophysical methods (electrical resistivity tomography – ERT and ground penetrating radar – GPR). The significance of piping in gully formation and hillslope hydrology has been discussed for many years, and most of the studies are based on surface investigations. However, it seems that most surface investigations underestimate this subsurface process. Therefore, our purpose was to estimate the scale of piping activity based on both surface and subsurface investigations. We used geophysical methods to detect the boundary of lateral water movement fostering pipe development and recognize the internal structure of the underlying materials. The survey was carried out in the Bereźnica Wyżna catchment, in the Bieszczady Mountains. (Eastern Carpathians, Poland), where pipes develop in Cambisols at a mean depth of about 0.7–0.8 m. The geophysical techniques that were used are shown to be successful in identifying pipes. GPR data suggest that the density of piping systems is much larger than that detectible from surface observations alone. Pipe length can be >6.5–9.2% (maximum = 49%) higher than what surface mapping suggests. Thus, the significance of piping in hillslope hydrology and gully formation can be greater than previously assumed. These results also draw attention to the scale of piping activity in the Carpathians, where this process has been neglected for many years. The ERT profiles reveal areas affected by piping as places of higher resistivity values, which are an effect of a higher content of air-filled pores (due to higher soil porosity, intense biological activity, and well-developed soil structure). In addition, the ERT profiles show that the pipes in the study area develop at the soil–bedrock interface, probably above the layers of shales or mudstones which create a water restrictive layer. Our results illustrate the suitability and limitations of GPR and ERT to study soil piping. In general, geophysical surveying is useful for gathering more information on pipe density, potential pipe detection, and recognition of the internal structure of materials underlying the pipes. However, the interpretation of radargrams and ERT profiles should be always accompanied by detailed terrain mapping due to potential disturbances affecting geophysical profiles.

1. Introduction

The significance of piping in landscape development and hillslope hydrology has been discussed since the 1960s (Bryan and Jones, 1997). Over the last decades, research has demonstrated that pipeflow can be a significant contributor to storm runoff in catchments (e.g., Uchida et al., 2001; Jones, 2010; Wilson et al., 2012). Moreover, it has been widely stated that piping plays important role in gully initiation and development (e.g., Starkel, 1960; Higgins, 1990; Bocco, 1991; Bryan and Jones, 1997; Faulkner et al., 2004; Faulkner, 2006, 2013; Verachtert et al., 2010; Zhu, 2012; Bernatek, 2015). Other authors have drawn attention to the relation between piping and landslides (e.g., Pierson, 1983; Uchida et al., 2001; Wilson et al., 2012; Verachtert et al., 2013). Piping can also lead to embankment dam failures (e.g., Foster et al., 2000a, 2000b; Fell et al., 2003; Richards and Reddy, 2007), with important implications for safety management (Fell et al., 2003).

Despite its importance, piping as a type of subsurface erosion caused by water flowing through the soil (Boucher, 1990; Jones, 1994, 2004) is still considered as one of the most difficult erosion processes to study. Piping is related to sapping, seepage erosion, and tunnel erosion (Dunne, 1990; Bryan and Jones, 1997; Fox and Wilson, 2010; Wilson et al., 2012). Sapping refers to mass failures or slumping resulting from undercutting of an embankment by seepage erosion (Fox and Wilson, 2010). Tunnel erosion involves the expansion of an existing conduit or a macropore primarily due to the shear stress exerted by flowing water (Bryan and Jones, 1997). However, the interaction of these processes is complex, and studying them in isolation may be

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http://dx.doi.org/10.1016/j.geomorph.2016.09.018
0169-555X/

virtually impossible (Bryan and Jones, 1997; Bryan, 2000; Jones, 2004). Several authors have attempted an in-depth discussion of the nature of piping and related processes (Dunne, 1990; Bryan and Jones, 1997; Fox and Wilson, 2010; Wilson et al., 2012).

Piping occurs below the soil surface, and evidence of this process become visible on the surface only when a pipe roof collapses, or a pipe inlet or outlet has been recognized (Czeppe, 1960; Galarowski, 1976; Jones, 1981; Verachtert et al., 2010, 2013; Bernatek, 2015; Bernatek-Jakiel et al., 2016). Therefore, mapping collapsed pipes (CPs) represent the most common field method of pipe detection. This method has been applied in a wide range of regions: in loess-mantled areas (e.g., Zhu et al., 2002; Zhu, 2012; Verachtert et al., 2010, 2013; Zhang and Wilson, 2013; Wilson et al., 2015), badlands (e.g., Farifteh and Soeters, 1999; Romero Díaz et al., 2007; Faulkner et al., 2008), peatlands (e.g., Jones, 1971; Holden and Burt, 2002), and in mountainous areas where pipes develop in Cambisols (e.g., Czeppe, 1960; Galarowski, 1976; Bernatek, 2015; Bernatek-Jakiel et al., 2016). To extend the field mapping of collapsed pipes, some authors used dye tracing (e.g., Jones and Crane, 1984; Smart and Wilson, 1984; Anderson et al., 2008; Wilson et al., 2015), or smoke bombs (Bíl and Kubeček, 2012). However, these are methods aimed at detecting the connectivity of soil pipes, rather than just finding new ones, and dye tracing is limited to the pipes in which water flows. Other approaches rely on destructive methods, such as soil coring or pit excavation (e.g., Botschek et al., 2002a, 2002b).

Pipe detection is methodologically challenging (Grellier et al., 2012). Researchers are aware that surface mapping and destructive methods as point-measurement techniques are not sufficient to identify and characterize a complete underground system (Cappadonia et al., 2015). They are also likely to underestimate network densities (Holden et al., 2002; Got et al., 2014). Jones et al. (1997) and Bryan and Jones (1997) highlighted that a major problem in the assessment of the role of piping is the difficulty of finding and defining pipe networks. Bryan and Jones (1997) underlined the need of new techniques for surveying pipe networks. Recently, Wilson et al. (2012) indicated that there is a need for non-destructive techniques to detect soil pipes and to monitor internal erosion and the evolution of soil pipes. The working hypothesis underlying this study is that shallow geophysical techniques may be useful to characterize pipe networks. Geophysics techniques have become increasingly popular in many geomorphological studies. An evaluation of geomorphological applications of geophysics (ground-penetrating radar – GPR, seismic refraction and direct current resistivity – DC resistivity) was presented by Schrott and Sass (2008). Common applications of these techniques include talus slope investigations (e.g., Otto and Sass, 2006), permafrost mapping (e.g., Vonder Mühll et al., 2002; Hauck and Vonder Mühll, 2003; Kneisel and Hauck, 2003; Kasprzak et al., 2016), alluvial deposits (e.g., Gourry et al., 2003; Froese et al., 2005; Podgorski et al., 2015), internal structures of landslides (e.g., Israil and Pachauri, 2003; Bichler et al., 2004; Perrone et al., 2004; Sass et al., 2008; Pánek et al., 2010; Migoń et al., 2010, 2014), and detection and characterization of cavities of different origin (e.g., solution or collapse sinkholes) in karst areas (e.g., Roth et al., 2002; Van Schoor, 2002; Ahmed and Carpenter, 2003; Carbonel et al., 2014).

Many researchers have also adopted geophysical survey methods to investigate the conditions of core materials in earth dams exposed to piping failure (e.g., Johansson and Dahlin, 1996; Panthulu et al., 2001; Titov et al., 2002; Oh and Sun, 2008). Electrical resistivity methods are particularly useful to this end, as they exploit the differences in electrical properties between water and soil (e.g., Panthulu et al., 2001; Sjödahl et al., 2005, 2009; Oh, 2012). Using these methods, researchers have effectively delineated weak zones in the core materials (Panthulu et al., 2001; Oh and Sun, 2008) and monitoring seepage (Johansson and Dahlin, 1996). However, the natural environment is both more varied and more complex than artificial embankment dams (Bryan and Jones, 1997).

To our knowledge, the first attempts to use non-destructive methods in pipe detection in the natural environment were made by Botschek et al. (2000) in loess areas in Germany (Bergisches Land), and by Holden et al. (2002) in peatlands in the UK. In both cases, they tested the usefulness of ground penetrating radar. Later on, Holden (2004) showed that GPR can help establish the hydrological connectivity of soil pipes when used in conjunction with tracers (e.g., sodium chloride). Got et al. (2014) are working on methods to improve signal processing, object detection, and system configuration in GPR in order to characterize subsurface networks in loessic areas (Eastern Belgium). In recent years, electrical resistivity tomography (ERT), seismic refraction tomography (SRT), and self-potential (SP) measurements have been used to detect sinkholes underlain by solutional conduits in mantled carbonate karst areas (Ahmed and Carpenter, 2003; Cardarelli et al., 2014; Giampaolo et al., 2016).

Despite these few attempts, the application of geophysics in the detection and characterization of piping systems in the natural environment has been scarce. Little is known about the density of piping systems in different regions, and it seems that most surface investigations lead to the underestimation of the process (Holden et al., 2002; Got et al., 2014). This study sought to better characterize piping systems in mountainous areas under a temperate climate using geophysical methods (ERT, GPR) and geomorphological mapping. The main goals were: (1) to estimate the scale of piping activity based on surface and subsurface investigations, (2) to detect the boundary of lateral water movement fostering pipe development, and (3) to recognize the internal structure of materials underlying the pipes. Moreover, a basic soil survey was conducted in order to assess the suitability of applying geophysical methods in given ground properties, as soil properties may affect the performance and interpretation of geophysical data (McNeill, 1980; Doolittle and Collins, 1995; Doolittle and Butnor, 2009). GPR is the most commonly used geophysical method in piping investigations, and ERT, hitherto rarely used, seems to be promising in piping research, especially to recognize the subsurface environment associated with changes of lithology, which may have an impact on pipe development.

2. Study area

The study area – the Bereźnica Wyżna catchment – is located in the Bieszczady Mountains, which are part of the Eastern Carpathians (Fig. 1). It is characterized by a temperate climate with a mean annual temperature ranging from 4.0 °C to 5.0 °C (Michna and Paczos, 1972), and a mean annual rainfall of 900–1000 mm (according to data from the Institute of Meteorology and Water Management – State Research Institute, IMGW–PIB, in Poland for the years 1960–2015 recorded at the Baligród–Mchawa and Terka weather stations). The Bereźnica Wyżna catchment (3.05 km^2, based on LiDAR data) represents a mountainous area with altitudes ranging from 502.1 m a.s.l. in the Gołosanka stream valley to 748.1 m a.s.l. (Markowska Mountain). The mean slope gradient of the study area is approximately 12°, and only 3.5% of the catchment has slope gradients above 30°.

Geologically, the Bieszczady Mountains are part of the Outer Carpathians consisting of folded Neogene formations; the youngest Carpathian Flysch, i.e., sandstones alternating with shales and mudstones (Haczewski et al., 2007). The Bereźnica Wyżna catchment is carved into the Oligocene–Lower Miocene Krosno beds of the Silesian Unit (Haczewski et al., 2007; Malata et al., 2014). This is a flysch facies showing the typical alternation of sandstones (from thin to thick-bedded) and shales and mudstones (Fig. 1C). These beds are quite silty compared to other Carpathian Flysch beds (Starkel, 1960). The rocks of the whole catchment are cut by a NE-SW fault, and they dip primarily to the SW (Fig. 1C).

The parent material for soils consists of slope deposits derived from the weathering of flysch rocks with a certain aeolian admixture (Kacprzak et al., 2015). The dominant soil group in the Bieszczady Mountains is the Cambisol (Skiba et al., 1998; Kacprzak, 2003; Skiba and Drewnik, 2003). Pipes develop in Cambisols between the B and C soil horizons (i.e., the soil–bedrock interface) (Bernatek-Jakiel et al.,