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Pore pressure profiling in Siercza landslide colluvium in the Carpathian flysch using a Cone Penetration Test (CPTU)

Jacek STANISZ[1], * and Zenon PILECKI[2]

[1] AGH University of Science and Technology, Al. A. Mickiewicza 30, 30-059 Kraków, Poland

[2] Polish Academy of Sciences, Mineral and Energy Economy Research Institute, Józefa Wybickiego 7 A,
31-261 Kraków, Poland

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This study identifies zones with significant changes in pore water pressure influenced by landslide processes. Measurements were taken in the near-surface strata of the Carpathian flysch, in colluvium of the Siercza landslide, near Kraków. Measurement of pore water pressure in flysch deposits is complicated due to the strongly heterogeneous properties of the medium and by variable water conditions, which are strongly influenced by rainfall intensity. Pore pressure profiling was performed in six series using a cone penetration test with a NOVA Acoustic cone. The tests were carried out in the colluvium to a depth of ~6.0 m under varying water conditions. The cone pore pressure results were compared to results of inclinometer measurements in the research area. Five zones with significant differences in pore pressure have been identified. Changes in both cone pore pressure and inclinometer displacement are evident at a depth range from 1.5 to 2.5 m. Two slip surfaces are likely present in this section. Such information can be used in engineering practice for more reliable assessment of slope stability in the Carpathian flysch.

Key words: cone penetration test, pore pressure, inclinometer displacement, landslide, colluvium, slip surface, Carpathian flysch.

INTRODUCTION

Pore water pressure provides essential information about the structure, properties, and physical-mechanical processes occurring in a geological medium. One of the possibilities of its measurements is the Cone Penetration Test (CPTU) (Lunne et al., 1997; Mayne, 2006; Robertson, 2009, 2016; Bajda et al., 2015; Tschuschke et al., 2015; Zawrzykraj, 2017; Młynarek et al., 2018). Moreover, analysis of pore pressure changes may indicate relation to the development of the landslide process (Wang and Sassa, 2003; Take et al., 2004; Schnellmann et al., 2010; Cascini et al., 2013). Studies on this issue have been conducted in the area of the Carpathian flysch (e.g., Zabuski, 2004; Pilecki et al., 2007; Stanisz, 2013, 2015; Bednarczyk, 2015; Harba and Pilecki, 2017; Stanisz et al., 2018; Kogut et al., 2018).

Some archil information concerning studies of cone pore water pressure in the Carpathian flysch deposits and the development of landslide processes was reported by Stanisz and Pilecki (2018).

Bednarczyk (2015) made pore pressure measurements in order to identify slip surfaces in landslides developed on flysch deposits near Gorlice, southern Poland. He developed a monitoring system consisting of pneumatic and vibrating wire sensors of pore pressure, inclinometers, piezometers and an atmospheric station. Bednarczyk (2015) noted that the development of deformation structures was associated with an increase in pore pressure in the range of 50–100 kPa. Pore pressure increase was particularly noticeable after intense rainfall in excess of 200–250 mm.

Zabuski et al. (2004) studied changes in water level content in flysch deposits relative to the intensity and duration of rainfall for several landslides in the region of Szymbark, southern Poland. He used 25 open piezometers and systems of inclinometers. Zabuski observed that displacements and changes in water level were related to the mechanical and hydraulic properties of the geological medium.

Similar studies concerning landslides in the Szymbark region were also made by Gil et al. (2009). They observed that the groundwater level decreased during brief rainfall episodes of

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* Corresponding author, e-mail: jacek.stanisz@gmail.com

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<30 mm, while for more intense rainfall >30 mm, the water level increased by 40–80 cm. An increase in inclinometer displacement of mass movement was also related to intense rainfall.

Stanisz and Pilecki (2018) provided results of four pore pressure profiles and inclinometer measurements in the near-surface colluvium of the Tęgoborze – Just landslide performed in dry and wet conditions. Pore pressure profiling was conducted by CPTU in the near-surface medium up to about 5 m depth. In dry conditions, the pore pressure varied from –82 to 48 kPa. In wet conditions with a varied degree of saturation, the pore pressure changed from –85 to 2 kPa. Significant changes in pore pressure values were measured in wet conditions as well as in dry conditions. Four zones of distinct pore pressure changes to a depth of ~5.0 m were determined. In these zones, inclinometer displacements of different values were registered. This information allows for the determination of weak zones in which the slip surface of a landslide might develop.

This study identifies zones with significant changes in piezocone pore water pressure in near-surface strata of Carpathian flysch influenced by landslide processes. The study was carried out in the colluvium of the Siercza landslide near Kraków in the southeastern part of Poland (Fig. 1). As context, we describe the geological engineering conditions in near-surface deposits of the Carpathian flysch in the Siercza landslide. The methodology of pore pressure profiling with its limitations is discussed. Finally, the results of piezocone pore water pressure together with inclinometer measurements are analysed in terms of the identification of a potential landslide slip surface.

LOCATION AND GEOLOGICAL SETTING

The Siercza landslide is situated on the northern slope of Siercza Hill that has a long, flat plateau (350–365 m a.s.l.). This area belongs to the northern part of the mesoregion of the Wieliczka Foothills, which extends W–E as a range of hills. Landslide Registration Card no. 819 was prepared for the landslide in an electronic database (Wójcik, 2017).

The Siercza landslide is located at the boundary between the Carpathian flysch and the Polish Carpathian Foredeep. This is the contact zone of the overthrust of the Subsilesian Nappe onto younger, clayey Miocene deposits. The synthetic geological profile consists of (Wójcik, 2017):

- variegated marls – Węglówka marls (Upper Cretaceous–Paleocene),
- sandstone and shale – Grodziskie beds and Upper Cieszyn shales (Valanginian–Hauterivian),
- sandstone, mudstone, shale, gypsum, anhydrite and halite – Wieliczka succession (Middle and Upper Miocene),
- silty clay (Miocene).

The landslide area is ~22.75 ha, ~621 m wide and 590 m long (Fig. 1A). The azimuth of the movement direction is close to 3°, and the average inclination is 9°. The landslide has a complex geological structure and it has been classified as of slide type. Actually, the landslide upper part is continuously active, while its lower part is inactive. The landslide tends to expand towards its upper part. This is especially visible in its western part. The main scarp has a height of 1–7 m. The landslide is located near to residential buildings.

The effects of mass movements are visible in the area of the landslide as characteristic morphological forms such as bulges, secondary scarps, thresholds, and basins without outflow (Fig. 1A, B2–B5). Folding and cracking are also visible on the surface of the main road 2027K and road 2034K (Fig. 1A). Along the road, there are cracks in the foundations and in the walls of buildings and fencing. In the central part of the landslide, there are many waterlogged places. The landslide is adjacent on its eastern side with another periodically active landslide (number 820).

The precise date of the landslide inception is unknown. Wójcik (2017) reported that it probably formed during the late glacial period or at the beginning of the Holocene. Mass movements usually follow intense rainfall. The landslide was periodically activated in 1997, 2007, and 2008. The saturation of the colluvium and plastic behaviour of the Miocene silty clays and variegated marl layers were the main reasons for mass movement. In 2006, soil was dumped in the area of the main scarp, which additionally loaded the landslide body. In consequence, many fractures occurred along the main scarp. In 2013, further mass movements took place which exposed the foundations of buildings located near the main road 2034K (Fig. 1A).

In 2008, Geological Company (PG S.A. from Kraków) drilled 15 boreholes to a depth of 15 to 17 m for the geological engineering characterization of the landslide (Jaskólski et al., 2008). In each of the 12 boreholes selected, an inclinometer and piezometer were installed. The drilling results showed that the flysch strata comprise shale with intercalations of thin-bedded sandstones of the Lower Cretaceous and variegated marls of the Upper Cretaceous. These strata are often folded with black clays of the Chodenice deposits (Miocene). The Quaternary is represented by silty clays and dumped soils, of varied thickness from 2.8 to 16.0 m in the upper part of the landslide. The colluvium consists of silty-clay deposits with thin sandstone intercalations.

Based on inclinometer measurements, two slip surfaces have been distinguished. The first of these was identified at a depth of 2.5–6.0 m. The second one was identified at a depth of 7.0–16.0 m (Fig. 2). In the upper part of the landslide, the deeper slip surface is located at a depth of ~13.6 m, and in the lower part it reaches a depth of 16.0 m (point I–6 in Fig. 2). In the lower parts of the landslide, the colluvium has an estimated thickness of ~20 m. Physical and mechanical parameters in geological engineering terms are distinguished on the Siercza landslide are shown in Table 1.

The landslide area is drained by the Serafa Stream, which is the right-bank tributary of the Drwina in the Vistula River basin. There is no continuous aquifer within the colluvium. Considerable infiltration occurs within the clayey colluvium and dumped soils. Water path flows are variable and dependable on the occurrence and intensity of rainfall as well as on the permeability of the flysch deposits.

METHODS

The pore water pressure profiling was carried out using a penetrometer with electrical piezocone of NOVA Acoustic of AB Geotech (Sweden) (Fig. 3). The pore water pressure is measured via a porous element installed at the shoulder between the cone tip and the friction sleeve (Fig. 3D). Pore water pressure values measured in the soil just behind the cone tip can be distinguished from the pore water pressure in hydrostatic stress conditions. An explanation of this effect can be given following Van Baars and Van de Graaf (2007). In a piezocone test, the surrounding soil is compressed by the penetration of the cone tip, which creates excess pore water pressure. At the same time, the shearing of the soil by the cone tip may also result in dilatant behaviour, which induces a negative excess pore pressure. Depending on the relative magnitudes of

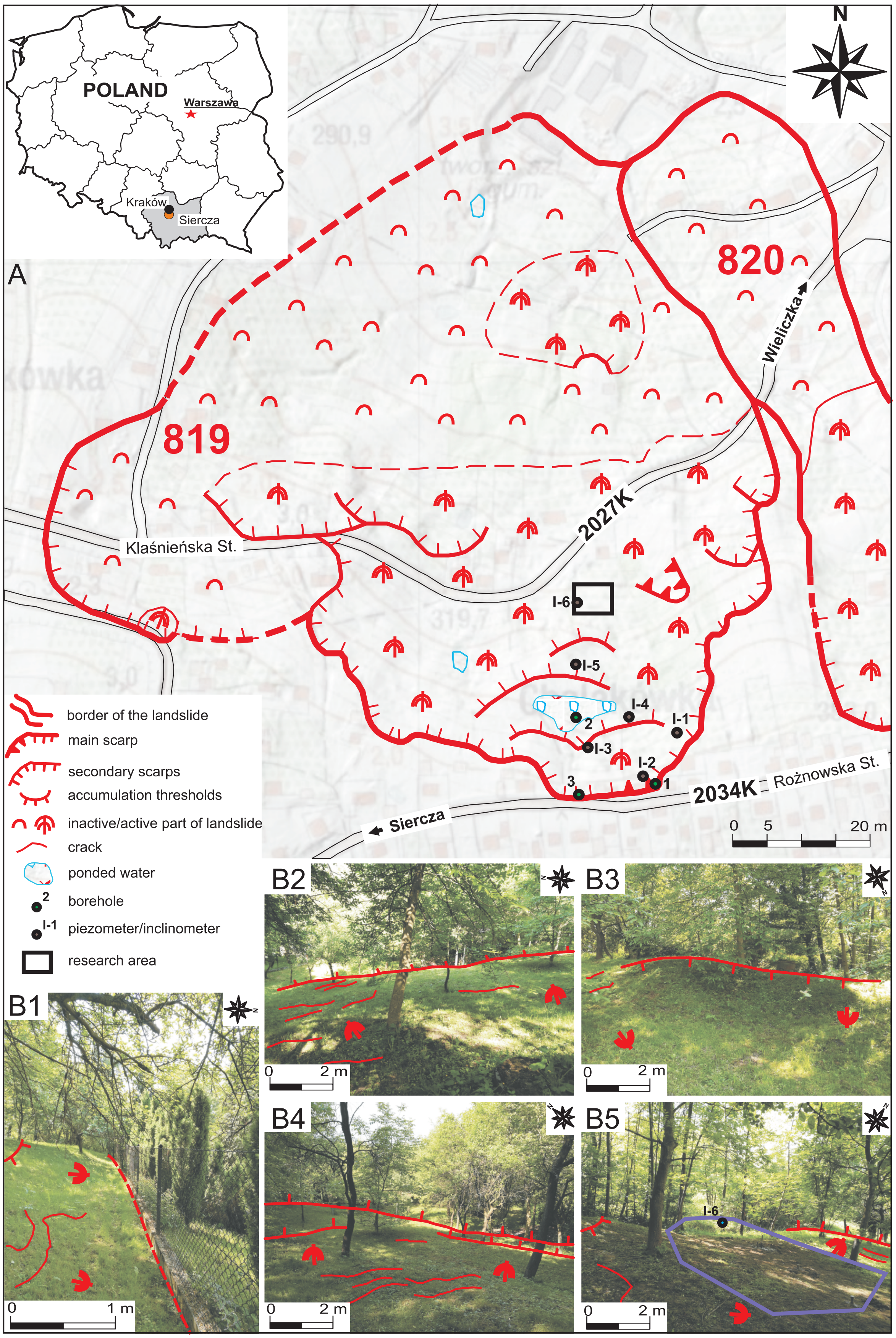

Fig.1. Location of research area in the Siercza landslide

A – map of the Siercza landslide, **B1–B5** – landslide forms

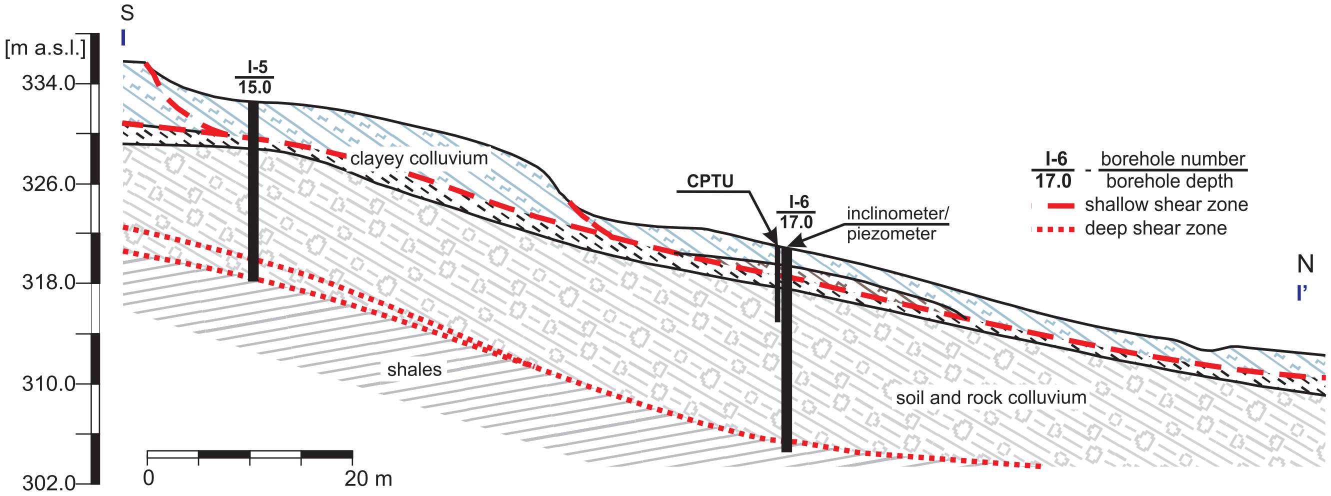

Fig. 2. Longitudinal geological engineering cross-section of the Siercza landslide (based on Jaskólski et al., 2008)

Table 1

Physical and mechanical parameters in geological engineering layers in the area of the Siercza landslide (based on Jaskólski et al., 2008)

Number of geol-eng. layer	Type of geological-engineering layer	Plasticity index	Bulk density [Mg/m^3]	Cohesion [kPa]	Angle of internal friction [deg]	Permeability coefficient [m/s]
I	soil colluvium: clSi	plastic	1.96	45	10	$1.43 \cdot 10^{-9}$
IIa	soil and rock colluvium: grSi	plastic	1.97	45	11	–
IIb	soil and rock colluvium: grSi	plastic/liquid	1.90	10	5	$8.13 \cdot 10^{-10}$
IIIa	soil and rock colluvium: clGr	semi-solid	2.10	110	12	$1.42 \cdot 10^{-9}$
IIIb	soil and rock colluvium: Cl+gr	plastic	2.08	55	6	$1.79 \cdot 10^{-8}$
IIIc	soil and rock colluvium: shales	plastic	1.90	50	5	–

clSi – clayey silt, grSi – gravelly silt, clGr – clayey gravel

the pore water pressure created by the compression and shearing, the resultant excess pore pressure may be less or greater than the initial hydrostatic pressure. In clean sands and gravels, an essentially drained response is observed and measured pore water pressure is about hydrostatic. In most other cases, an initial undrained response occurs that is followed by drainage. Once penetration has stopped, the excess pressure will dissipate with time and tends to the hydrostatic value.

Using a piezocone we can also measure point resistance and sleeve friction. When the piezocone is pushed into the ground, the total force acting on the cone induces a cone resistance q_c. The total force acting on the friction sleeve induces the sleeve friction f_s. Based on piezocone parameters, many methods have been developed for soil type determination (e.g., Senneset et al., 1989; Eslami and Fellenius, 2004). Among them, Robertson et al. (1986) introduced a pore pressure ratio B_q as follows:

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_v} \qquad [1]$$

where: u_2 – pore pressure measured at cone shoulder, u_0 – hydrostatic (initial) pore water pressure, q_t – cone resistance corrected for pore water pressure on shoulder, σ_v – total overburden vertical stress.

The pore pressure ratio B_q allows for the determination of soil type based on a combination of piezocone parameters as shown in Figure 4. In our study we would consider only piezocone pore pressure in the context of degree of saturation and water path flows in the landslide body. Nevertheless, we show the relationship between the piezocone parameters to indicate how complex it is. Analysis of the point resistance and sleeve friction response is beyond the scope of this study.

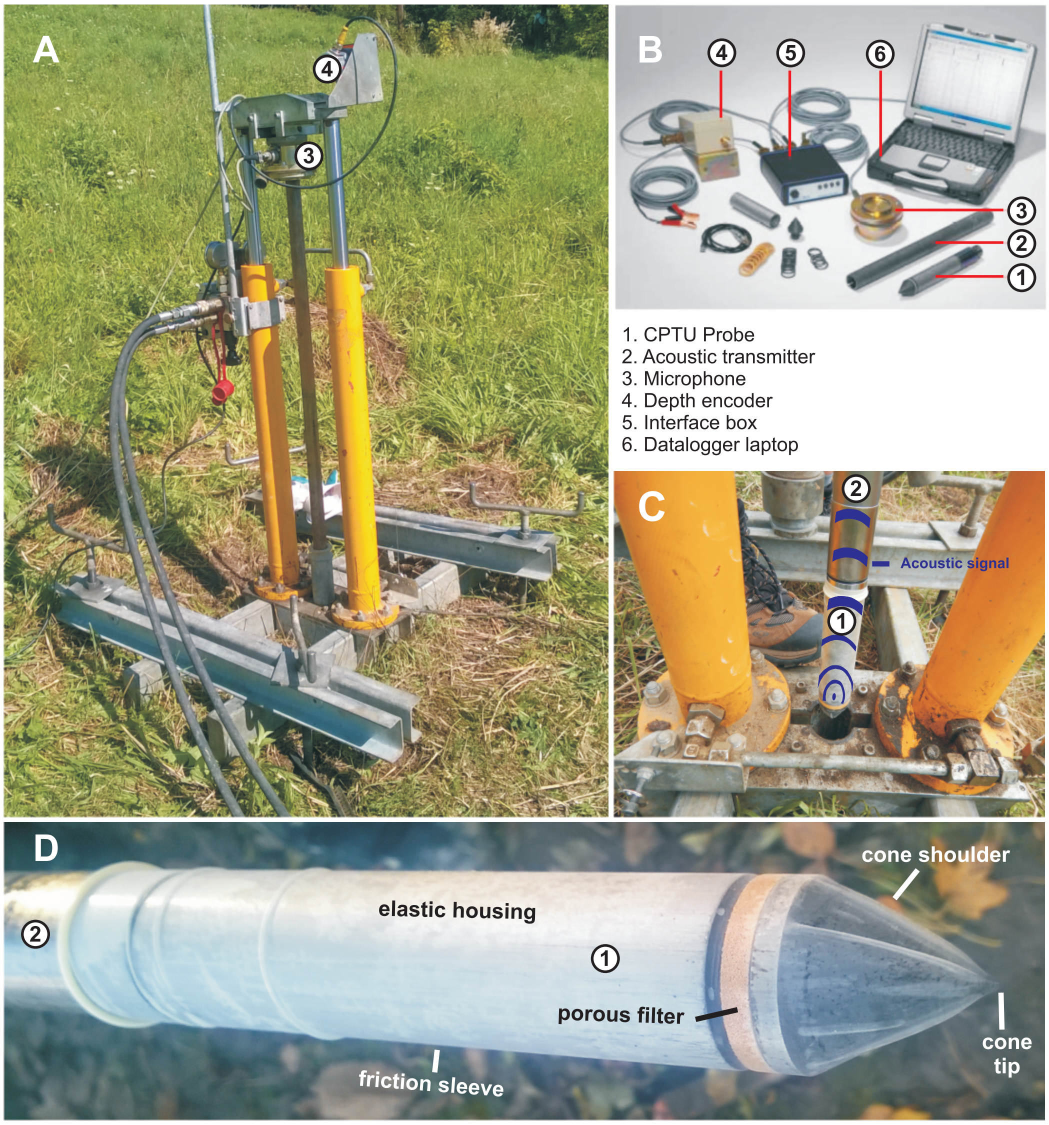

Fig. 3. CPTU probe used in measurements (phot. Stanisz and Pilecki, 2018)

A – general view, **B** – elements of the measuring set, **C** – CPTU probe, **D** – CPTU piezocone with elastic housing

The study was conducted in the central part of the Siercza landslide near the main road 2027K, and near point I–6 (Fig. 5). This point consists of two boreholes used for piezometric and inclinometer probes. The inclinometers had two components: X in the perpendicular and Y in the parallel direction to the axis of the landslide. In the central part of the research area, a borehole S-1 was made to a depth of 5 m (Fig. 5). In its vicinity, 6 CPTU measurements were made out to a depth of ~6 m. During the CPTU test, the water table was measured in each of piezometers P1–P5 (Fig. 5A, B).

The measurement procedure consisted of (Stanisz and Pilecki, 2018):

- preparing the measuring set for work – anchoring and levelling;
- preparing a de-aerated porous filter before measurement. The filter was protected in a container filled with glycerol. Venting the measuring chamber and filter assembly. Connecting the transmitter with the cone and securing the tip with a thin insulated housing;
- Performing a “zero” measurement;
- Profiling of the pore water pressure. Using the piezocone we also measured point resistance and sleeve friction;
- Performing a “zero” measurement after profiling.

The measurement procedure was repeated using a new porous filter each time. The measurement of the pore pressure was carried out every 2 cm. The velocity of piezocone advancement was ~2 cm/s.

Six field measurements were carried out in the period 2017–2018. The first three were made in dry conditions – 1a (17 November, 2017), 2a (8 November, 2018) and 3a (12 November, 2018). The next three were carried out under saturated conditions – 1b (20 September, 2017), 2b (12 July, 2018) and 3b (2 November, 2018). A day before measurement 1b, there was intense rainfall of 336 mm. One day and two days earlier, it was 2 and 7 mm, respectively. Early in the morning of 12 July, 2018 (measurement 2b), there was rainfall of 42 mm. The day before it was 46 mm. The last measurement (3b) was made

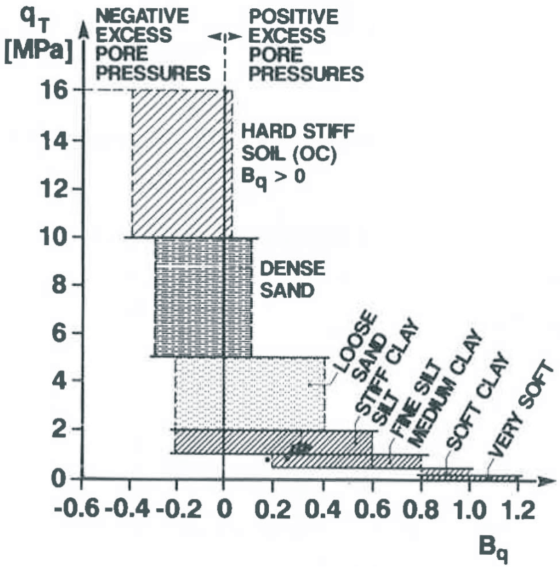

Fig. 4. Classification of soil type on the basis of the pore pressure ratio B_q and cone resistance q_t (Senneset et al., 1989)

All symbols are explained in the text

when the rainfall was low. On November 2, 2018 it was 2.6 mm, while on the previous day it was 0.7 mm.

Due to the specifics of the measurement of piezocone pore water pressure, we expected to obtain information concerning the location of greater saturation zones or water flow paths. The zones identified may be related to the development of slip surfaces in the geological medium. The history of saturation and insolation have not been included in the analysis.

RESULTS AND ANALYSIS

The results of the inclinometer measurements made it possible to determine the location of the slip surface. At point I–6, evident slip surfaces occur at depths of ~2.5 and 16 m. Smaller displacements were also observed at depths of 8.5 and 12 m. The largest increases in inclinometer displacements with a maximum value of 1.1 cm occurred at a depth of 2.0 m in the NNE direction.

Piezometric measurements showed that the depth of groundwater level varies from 0.4 m to ~1.9 m. In dry conditions, the depth of groundwater varied from 1.5 to 1.9 m, and in saturated conditions the depth varied from 0.4 to 0.6 m.

The results of the piezocone pore pressure profiling together with inclinometer displacement measurements are shown in Figure 6. Figure 6A shows six curves of piezocone pore pressure profiling and a curve of their relative pore water pressure u_2^R. This parameter u_2^R was calculated as the normalized sum of all absolute values of pore pressure to total vertical stress, similarly to geophysical anomaly (Szreder et al., 2008), as follows:

$$u_2^R = \frac{i\sigma_v - \sum |u_{2i}|}{i\sigma_v} \cdot 100\% \qquad [2]$$

where: u_{2i} – pore water pressure measured at a given depth, i – number of pore water pressure measurements at a given depth, σ_v – total vertical stress at a given depth.

The parameter u_2^R defines how great is the pore pressure anomaly measured in different conditions compared to total vertical stress and expressed as a percentage.

Figure 6B shows curves of the parameter u_2^R and inclinometer displacement in two perpendicular directions. The displacement was measured after each pore pressure measurement at the I/6 measuring point. Figure 6B also shows the theoretical curve of maximum hydrostatic pressure changes with depth based on piezometer measurements.

In general, the piezocone pore water pressure for all six measurements ranged from 102.2 to 59.7 kPa. The maximum positive value of the pore pressure was registered in the near-surface zone (up to 10 cm) and in the upper part of geological engineering layer I. The maximum negative value was recorded in dry conditions at a depth from 3 to 6 m. In this zone, there are clays or clayey gravel in a semi-solid condition. The greatest values of inclinometer displacement were recorded at a depth of 2 m.

The results of piezocone pore pressure measurements were analysed for significant positive or negative changes. We assumed that such anomalous changes may be associated with significant changes in water content and may indicate the presence of weak zones. In both Figure 6A, B, five zones of anomalous changes in pore pressure can be distinguished. These are numbered from 1 to 5:

- Zone 1 – this was recognized at a depth of 1.5–1.7 m (Fig. 6A). In this zone, an increase in the piezocone pore pressure value was clear. In dry conditions it reached a maximum value of 59.7 kPa. In saturated conditions it reached 48.5 kPa after a rainfall of 336 mm. This increase in the pore pressure value was observed in two measurements. In the remaining four cases, both for dry and saturated conditions, an increase in pore pressure in the range of 1.8–8.0 kPa was measured. In zone 1, silty clay with rock fragments in a plastic consistency was penetrated. This layer was also characterized by the greatest increase in displacement of the X (10 mm) and Y (5 mm) directions. Presumably, this zone contained an active slip surface; it was also documented by Jaskólski et al. (2008).
- Zone 2 – this was recognized at a depth of 2.0–2.3 m. For two measurements, a small increase in pore pressure was registered. In dry conditions, it reached a value of 9.6 kPa. After rainfall of 2.6 mm, the increase reached a value of 42.3 kPa. In this zone, inclinometer displacement took place in the direction down the slope and reached a value of ~2 mm. In this zone, the increase in pore pressure was associated with the occurrence of clay with sandstone fragments and varied with different water flow paths.
- Zone 3 – this occurred at a depth of 2.5–2.6 m. In this zone, an increase in the piezocone pore pressure was registered for five measurements. In dry conditions, the pore pressure was in the range of –2.2–24.7 kPa. In saturated conditions, the pore pressure was 31.7 (rainfall at value 46 and 42 mm) – 38.8 kPa (rainfall at value 336 mm). Archival study showed that at this depth the slip surface in the upper part of the clay layer with the rock fragments in the plastic state was occurred (Jaskólski et al., 2008). This was not clearly confirmed by inclinometer measurements.
- Zone 4 – this occurred at a depth of ~3.0 m. In clay in a semi-solid/plastic condition, a suction pressure of –60 kPa was registered. For four measurements, there was an increase in pore pressure in the range of 3.9 to 9.8 kPa for saturated conditions, and –6 to –2 kPa for dry conditions. In this zone there were small inclinometer displacements up to 1 mm for the X direction.

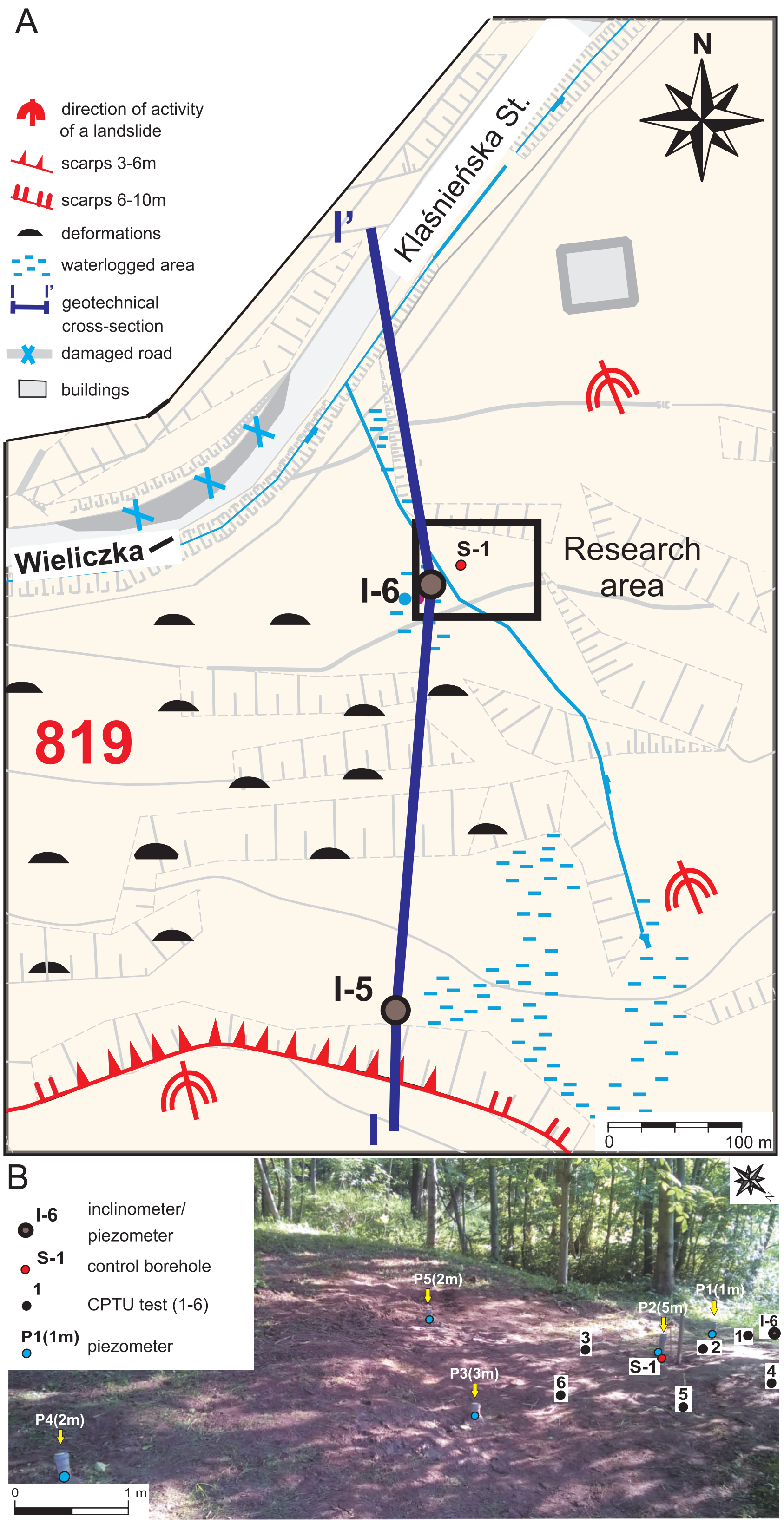

Fig. 5. Location of research area in the Siercza landslide with measurement points

A – part of the landslide map, **B** – location of the measurement points

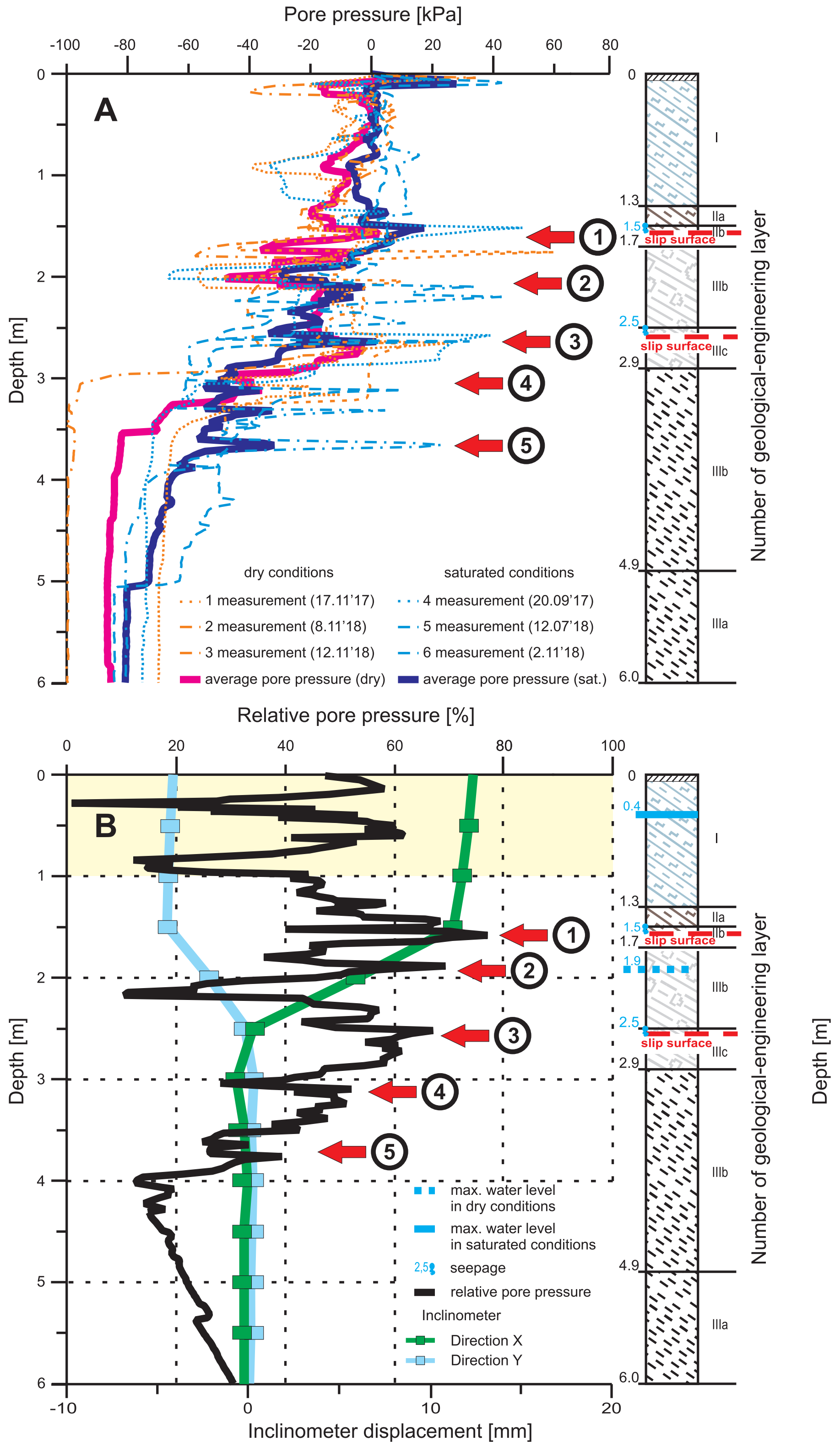

Fig. 6. Graphs of piezocone pore water pressure profiles and inclinometer displacement along geological engineering profile S-1

A – results of six measurements of pore pressure and average of pore water pressure u_2 in dry and saturated conditions; **B** – results of inclinometer displacement and relative pore water pressure u_2^R; for other explanations see Figure 2

- Zone 5 – this occurred at a depth of ~3.6 m. Suction pressure dominated in this zone. In dry conditions, it was from –100 to –65.4 kPa. In saturated conditions, it ranged from –71.8 to –46.1 kPa. The exception was one measurement, in which there was an increase in the pore pressure of 22.7 kPa after rainfall of 2.6 and 0.7 mm. Presumably, this increase was related to the presence of clay with shale and sandstone fragments. In zone 5 there was no inclinometer displacement.

Significant anomalies of pore pressure are observed in the near-surface zone at a depth of up to ~1 m, shown in yellow in Figure 6B. The cause of these anomalies may be the high sensitivity of pore pressure to rainfall in this zone. The root systems of vegetation may also have significance regarding the random distribution of pore pressure.

CONCLUSIONS

Measurement of piezocone pore water pressure in the strongly heterogeneous colluvium of the Carpathian flysch is difficult to perform and interpret. These difficulties arise from unstable water level, strongly changeable permeability and complex water flow paths in a medium containing rock fragments. Water level are also strongly dependent on the occurrence and intensity of rainfall.

Based on the piezocone pore pressure and inclinometer displacement measurements in the colluvium of the Siercza landslide, the following conclusions may be drawn:

- CPTU tests enabled pore pressure profiling up to a depth of 6 m. In dry conditions, the pore pressure value ranged from –102.2 to 59.7 kPa. For varying water saturation, pore pressure value ranged from –84.2 to 48.5 kPa.
- Five zones of anomalous changes in pore pressure were determined, as shown in Figure 6. These zones were partly confirmed by inclinometer displacements that occurred up to a depth of 3.5 m with a maximum of ~10 mm at a depth from 1.5 to 2.5 m.
- Changes in both piezocone pore pressure and inclinometer displacement are evident at a depth range from 1.5 to 2.5 m (zone 1–3). Two slip surfaces are probable in this section (Fig. 6B).
- In the remaining sections, characteristic changes in pore pressure were registered, but no distinct inclinometer displacement occurred. Probably, the deformation process has just started in such zones.

The relationship between the change in pore water pressure and the development of landslide processes is complex. Piezocone pore pressure profiling may be useful to more reliably determining the location of the slip surface. This information can be used in engineering practice for more reliable assessment of slope stability in the Carpathian flysch.

The study provides only qualitative information about this relationship and further research within different Carpathian flysch settings is required.

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