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Landslide processes in a flysch massif — case study of the Kawiory landslide, Beskid Niski Mts. (Carpathians, Poland)

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Geological setting and precipitation triggers seem to be obvious parameters controlling landslides, but their relation to individual sliding processes has not been clear. We take on interdisciplinary approach (combining Earth science methods with an engineering-geotechnical approach) to examine sliding processes in the Kawiory landslide in the Polish Carpathians. Field parameters were obtained from inclinometer monitoring, meteorological records, piezometer data and geomechanical tests. Numerical simulation of the landslide development was performed, both for the reconstruction of the internal deformation phenomena on the slope and for approximate prediction of its future behaviour. An empirical formula describing the relationship between the depth of groundwater level (GWL) and precipitation is presented. The case study showed that for the observed quasi-continuous creep, the depth and in particular the intensity of GWL fluctuations might be crucial.

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Key words: Carpathian Flysch, landslide, monitoring, numerical simulation.

INTRODUCTION

Numerous landslides have been reported in the Western Carpathians. The tectonic and lithological (flysch) structure combined with precipitation triggers means that this region is prone to mass movements (e.g., Nemčok, 1972; Starkel, 1997; Krejči *et al*., 2002; Rączkowski and Mrozek, 2002; Margielewski, 2004; Wójcik *et al*., 2006). The Beskidy, important ranges of the Carpathians, are not exceptional in this respect. This paper analyses landsliding processes on an experimental slope, located in the Beskid Niski Mts., in the vicinity of Szymbark village near Gorlice city. The slope selected and Kawiory landslide occurring there are representative of this region (Dauksza and Kotarba, 1973; Zabuski *et al*., 1999). Similar forms have been observed in extensive parts of the Beskidy ranges and in the Carpathian Foothills (Mrozek *et al*., 2005; Wójcik *et al*., 2006).

The idea of this study arose from a critical assessment of the results of landslide processes recognized in the Polish Carpathians. Usually, such research has been either based towards an Earth science or — to a lesser extent — towards an engineering (geotechnical) approach. Following the first line of reasoning, a given object is characterized by its geology, geometry and qualitative assessment of passive (causative) factors that influence the initiation and development of sliding. Simultaneously, simplified structural models are built, in which a “slide surface” is treated as a discrete surface separating a moving mass (e.g., colluvium) from stable bedrock. The second, engineering (mainly geotechnical), approach, drawing partially upon a primary environmental-geological assessment and upon simple 2D numerical models and analyses, concentrates on stability calculations. Unfortunately, complete reconstruction of a slope failure is unattainable and, therefore, the real sliding process is drastically simplified or even erroneously dealt with in certain cases. For example, treating the sliding rock mass as a rigid body, as practised in stability analyses by limit equilibrium methods (e.g., Bishop, 1955; Madej, 1981), is far from the complex reality. In order to overcome such deficiencies, in this study reconstruction of the deformation process has been performed considering the elastic-plastic and elastic-visco-plastic behaviour of a soil-rock medium and using an advanced finite difference method. Geomechanical and numerical models have been constructed and calibrated on the basis of the results both from geological and geotechnical investigations performed on the slope. The results of numerical simulations of the deformation processes have been tested by comparison with displacements measured in the boreholes by inclinometric methods. The superficial displacements (retrieved from GPS measurements) also have been taken into account.

SCOPE AND METHODS OF STUDY

The research methods were selected as to be complementary, thus the results of geological and geomorphological examinations were compared with those from engineering-geotechnical tests and numerical simulations, and *vice versa*. The studies involved:

— examination of geological and hydrogeological conditions as well as physical and mechanical parameters of soils and rocks composing the slope;

— measurements of underground displacements in boreholes, using an inclinometer probe;

— GPS measurements;

— quasi-continuous measurements and systematic interpretation of meteorological factors as well as records of ground water level (GWL) using piezometers;

— numerical simulations of slope deformations taking into account the rheological behaviour of the soil-rock medium.

The geological setting of the test area was recognized based on field mapping, analysis of archive documentaries and interpretation of cores obtained from 4 exploratory boreholes (depths 8.7 to 30.8 m). Laboratory geotechnical tests of the sampled cores provided additional information on the properties of the slope massif.

Slope deformations were measured by the inclinometer method (Zabuski, 2004; Stark and Choi, 2008) in the boreholes. Four boreholes were located from the top to the base of the landslide in order to gain insights into the deformation mechanism in various parts of the landslide. The measurements were taken at time intervals of a month at average, and in this way almost-real-time displacement records were obtained for comparison with hydrometeorological data.

Meteorological and piezometric records were collected to determine the influence of hydrometeorological conditions on the dynamics of mass movement. The meteorological parameters were recorded at the Research Station of the Institute of Geography and Spatial Organization, Polish Academy of Science (IGSO PAS) at Szymbark, located *ca*. 500 m away from the experimental slope. Thus, the results obtained should represent adequately conditions on the landslide slope.

The results of geomechanical modelling and numerical simulations of the landslide development provide, firstly information on deformation mechanisms, whose measurable outcomes are slope displacements. Secondly, they show the influence of passive (i.e. lithology, tectonics) and active (precipitation, groundwater fluctuations) factors on the mass movement. The geomechanical model that takes into account the viscous behaviour of the medium (except for elastic and plastic phenomena) was calibrated by comparing the displacements derived from numerical simulation and obtained by measurements. Such a calibrated model served as a tool for approximate prediction of future displacements. Drawing from that, numerical analysis allows a more thorough investigation of the landslide in terms of its description as an object (static approach) and as a process (dynamic approach). Numerical simulation was carried out using a *FLAC 4.0* programme (Itasca, 2000) based on a finite difference method in plane strain conditions (2D). The main features which make this programme particularly suitable for solving deformation and stability problems in geologic framework are as follows:

— considering non-elastic (plastic in particular) behaviour of the medium as well as modelling its heterogeneity;

— solving time-dependent problems; i.e. viscous behaviour of the medium;

— solving incremental problems, i.e. considering development phases of the observed process and the associated changes of stress.

STUDY AREA

LOCATION

The study area (Fig. 1) is located close to the IGSO PAS Research Station at Szymbark near Gorlice, just at the boundary of two large geomorphological units: the Beskid Niski Mts. and the Jasło–Sanok Depression (Starkel, 1972). The variety of regional relief is shown in height differences between elongated ridges of medium-high mountains (600–750 m a.s.l), foothills (450–550 m a.s.l.) and valley floors (300–350 m a.s.l.). The altitudinal arrangement generally reflects the tectonic development. Commonly, slopes are steeper in the Beskidian part (reaching over 25–30^{o}) while gentler inclinations are typical of the foothills level. The natural drainage network has a rectangular pattern, thus gorge sections in consequently dissected ridges can be identified. This is the case of the Ropa River, close to Szymbark.

The area of interest focuses on the south-facing slope of the flattened ridge of Taborówka (422.6 m a.s.l.), which is occupied by an extensive morphological form known as the Kawiory landslide (Figs. 1 and 2). The latter reflects a series of slide events, which have been transforming the slope. The resultant composite morphological form, extending from the ridge-crest to the bottom of the Ropa valley (*ca*. 300 m a.s.l), has demarcating features bearing the closest resemblance to the compound landslide in the mass movement classification (Dikau *et al*., 1996), and is referred to as the landslide system throughout this paper.

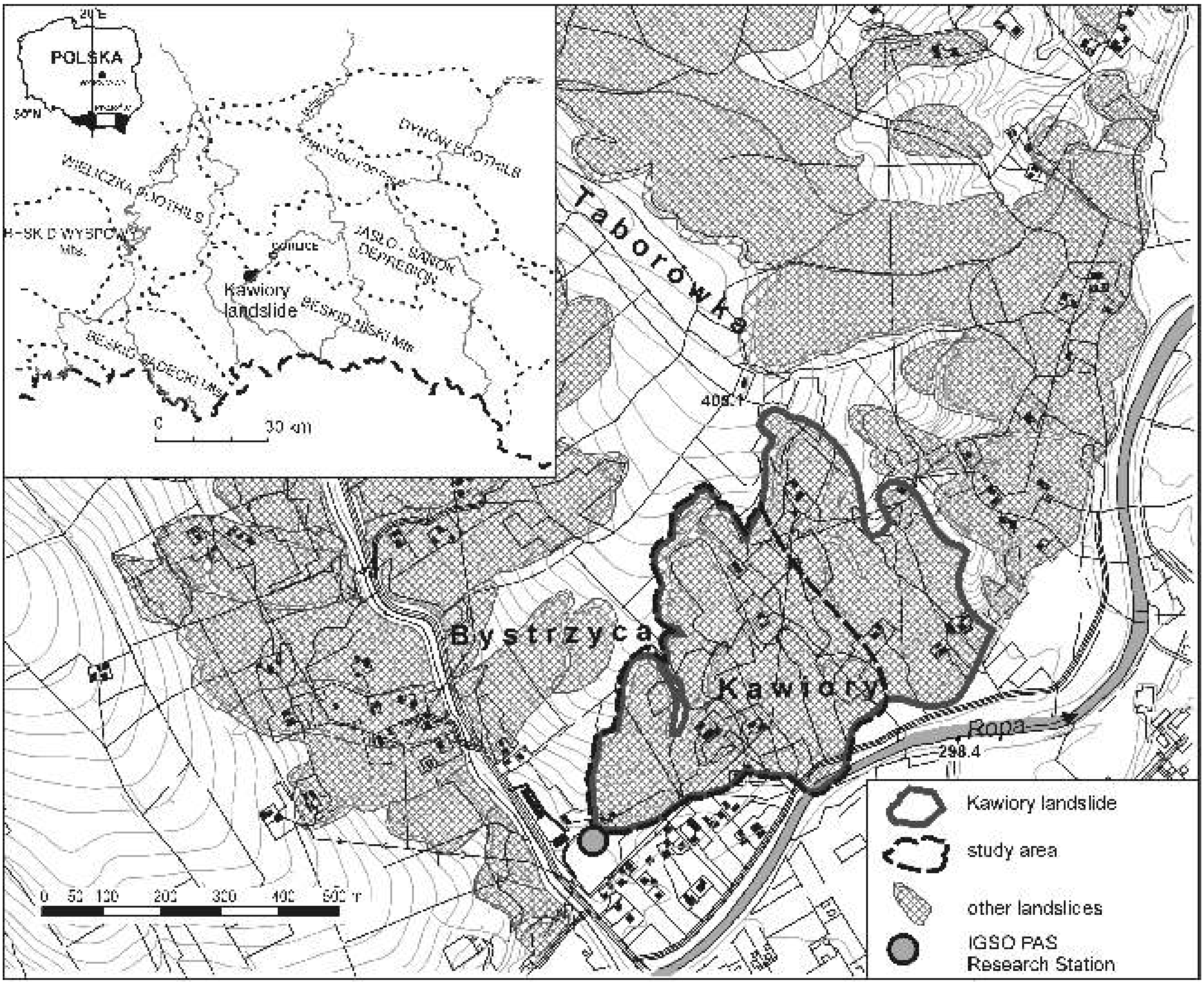

Fig. 1. Study area

GEOLOGICAL SETTING

The Kawiory landslide is located in the marginal zone of the Magura Unit, where it horizontally thrusts over the Silesian Unit. The front of this overthrust is found east of the area studied near Gorlice (Świdziński, 1973). The thickness of the Magura series in this zone varies from several dozens to 300–500 m. The ridge of Taborówka comprises rocks of the Magura succession of Upper Cretaceous to Eocene age. The rocks include the Inoceramus Beds and variegated shales (Figs. 3 and 5) overlain by Quaternary deposits. The latter consist of clays, loams and loams that include debris of various origin, including landslide colluvium, as well as river alluvia which occur in the valley of the Ropa River.

The Inoceramian Beds are exposed in the main scarp of the Kawiory landslide and in the channel of the Bystrzanka Stream flowing nearby. The beds are developed as thin- and medium-bedded sandstones and shales. Grey-blue and locally greenish sandstones are hard while their fractures are often filled with calcite. The sandstones are intercalated with clayey shales of variable thickness. The shales, usually dark grey and black or occasionally green-grey, are weakly calcareous or non-calcareous. Marl intercalations occur here only sporadically. There are roughly equal proportions of sandstones and shales, so these beds are often referred to as "normal flysch" (Bober and Zabuski, 1993). At the upper face of the Inoceramian Beds, however, thick-bedded, medium-grained (sporadically coarse-grained) sandstones predominate in places and are visible in the region of the landslide main scarp.

The Inoceramian Beds are capped by Eocene variegated shales. The latter, developed as clayey shales, are dark-grey, red, green, blue and grey. They represent weakly resistant clayey-shale flysch in which sandstones, usually green, occur sporadically as individual layers, a few centimetres thick. The variegated shales crop out at the surface near the eastern margins of the Kawiory landslide as well as being present in the bedrock (Fig. 3).

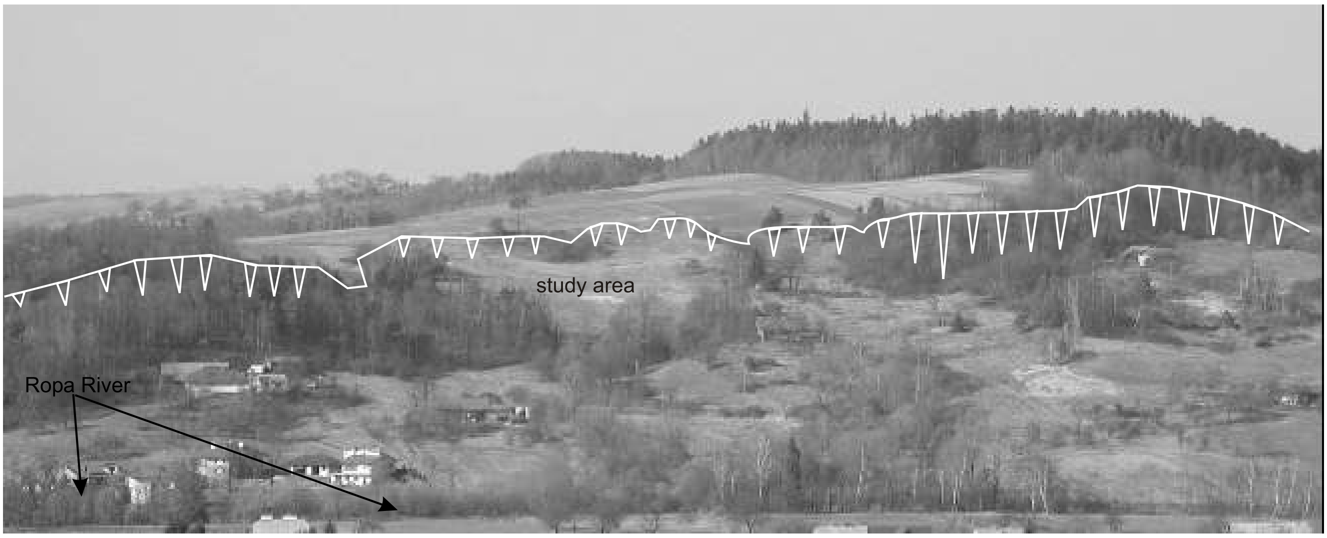

Fig. 2. Kawiory landslide (seen from the south)

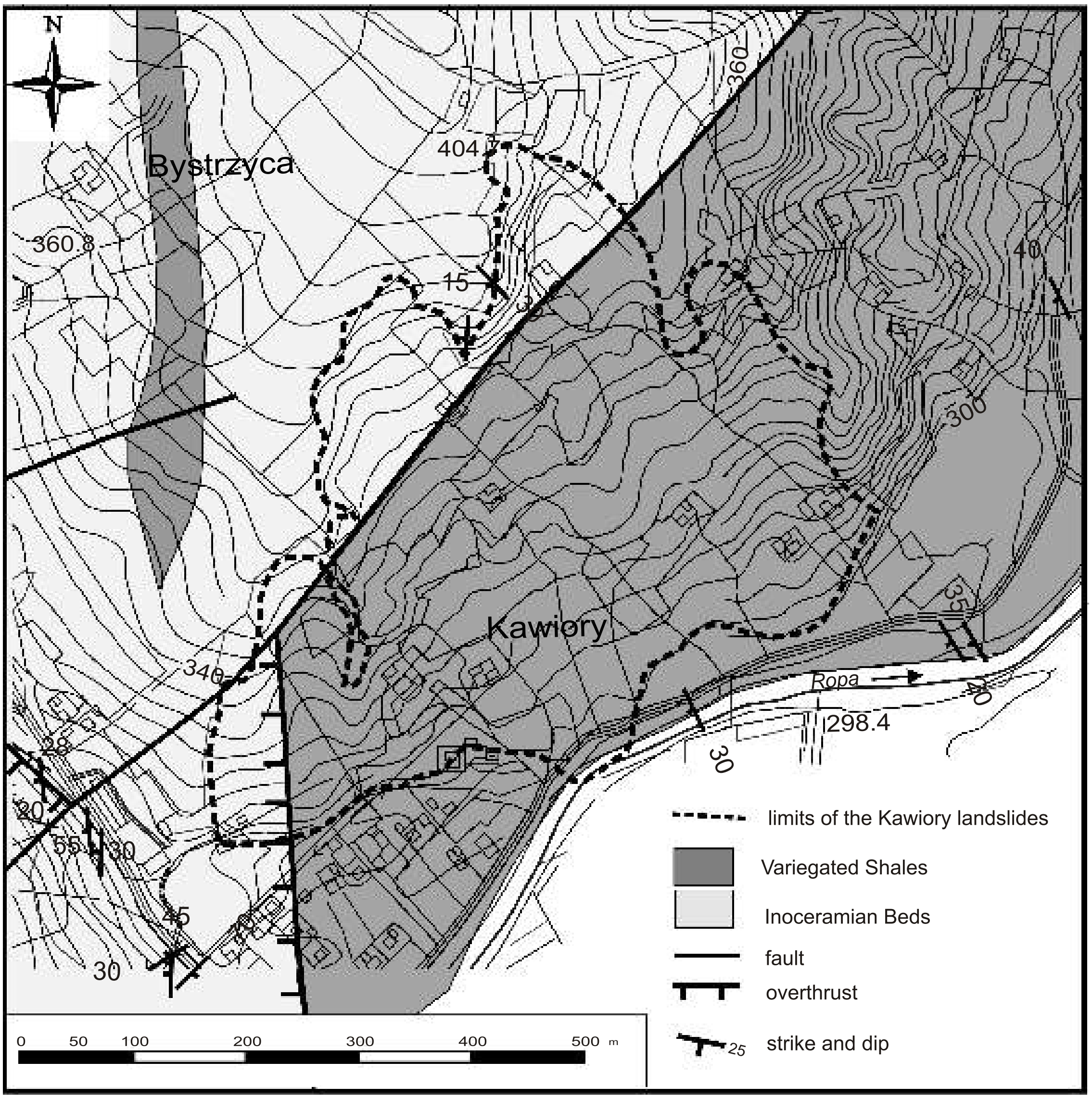

Fig. 3. Geological sketch and Kawiory landslide system (after Wójcik, 2002)

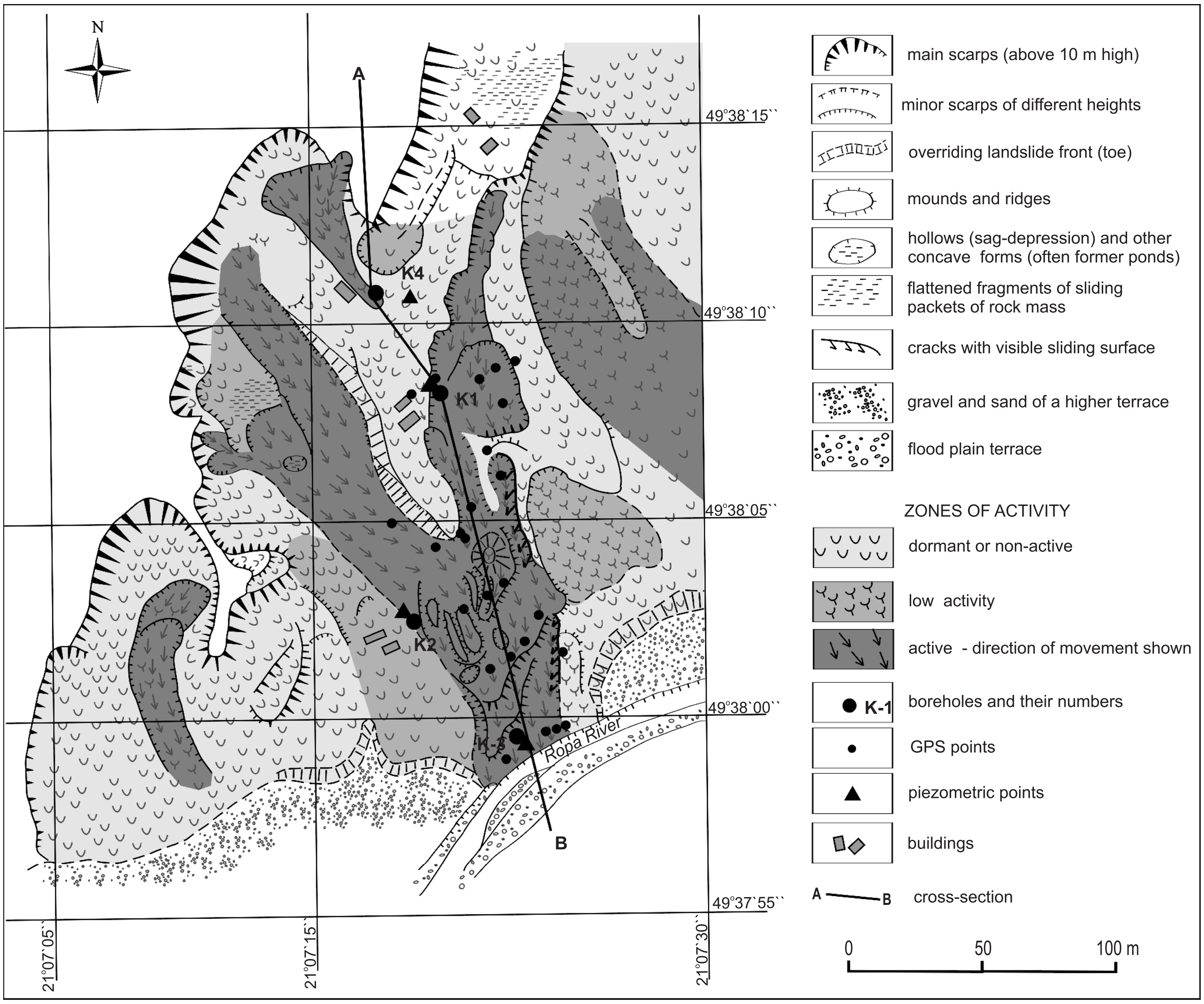

Fig. 4. Kawiory landslide system

The landslide bedrock is strongly tectonised, a state related to the neighbouring Magura overthrust and to the small thickness of the Magura series. One of the larger dislocations running across the landslide is the system of the Ropa River Fault (Świdziński, 1973). The fault is approximately NE–SW oriented and occurs in the upper part of the Kawiory landslide. Along the fault the Inoceramus Beds come into contact with the variegated shales (Fig. 3). The northern block is upthrown. Individual rocks units have additionally been sliced and imbricated. A few small slices are likely to occur in the bedrock of the landslide. In the western part, the Inoceramus Beds override the variegated shales, as seen in boreholes (Świdziński, 1973). Here, the overthrust is oriented almost N–S.

LANDSLIDE DESCRIPTION

Detailed studies have focused on the western portion of the Kawiory landslide system, which starts at an elevation of 387 m a.s.l. and has a distinct, 10–12 m — high main scarp (Fig. 4). The landslide tongue (front 1–4 m high) rides over the upper terrace of the Ropa River, while in the eastern portion of the area studied, it descends to the river channel (297.5 m a.s.l.) as a narrow strip, *ca*. 100 m across. The height difference between the edge of the scarp and the river channel is 90 m. Steps, flattened areas, bulges, ridges and depressions occur in the landslide body. The most extensive flattened area is found in the northeastern part of the landslide, directly below the high main scarp (Fig. 4). The depressions are filled with water only after intensive rainfall or thawing events. At the time when the studies were performed, a slip surface with scratches was exposed. Between the marginal cracks and slide steps, in the area of the tongue, longitudinal and transverse tension cracks as well as push-ridges and mounds occur. The bending direction of the ridges and transverse cracks shows the movement direction.

As seen from topographic maps, the Kawiory landslide was formed before 1900, with its subsequent activity varying as re-

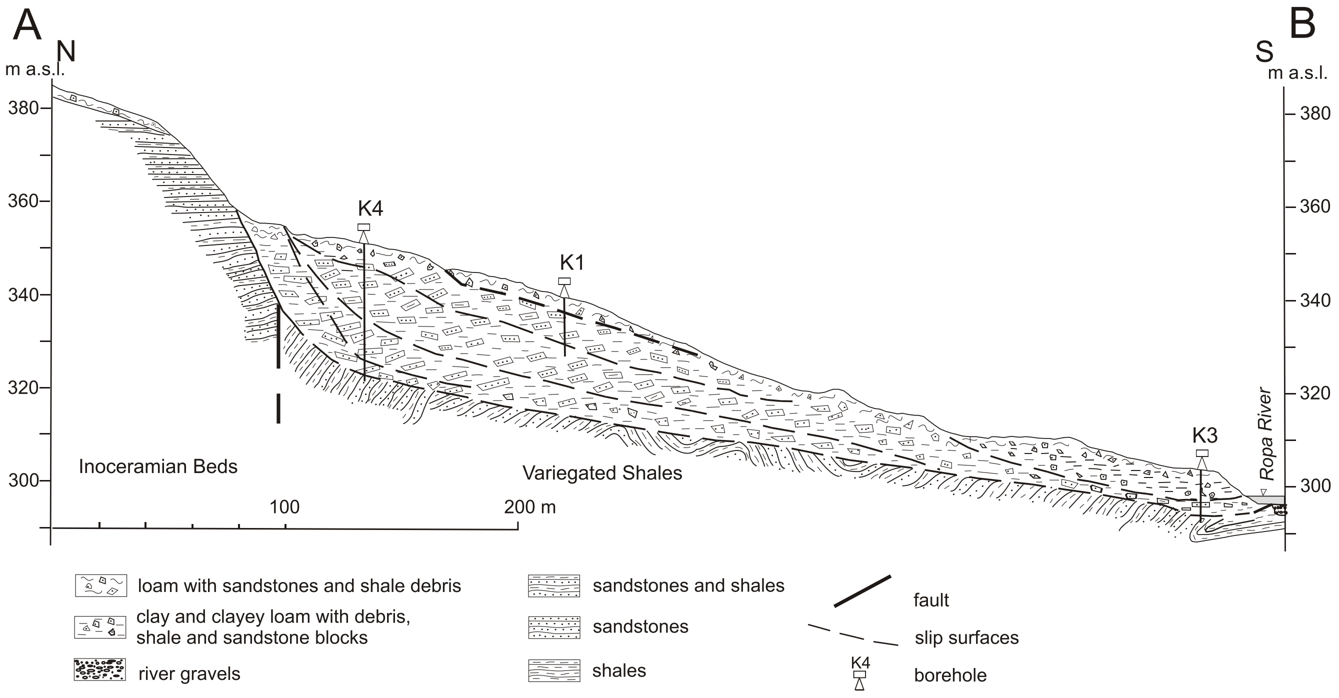

Fig. 5. Geological cross-section of Kawiory landslide

A, B — location as in Figure 4

gards intensity of movement and location of individual slip events (Dauksza and Kotarba, 1973). Because of that, it may be considered as a complicated landslide system rather than as a singular slide. Present-day landslide activity is shown an surface deformations (Fig. 4). The latter manifest themselves as furrows and bulges, which form undulose belts with numerous open cracks. Traces of present-day movements are also visible in vegetated terrain. Trees and bushes are displaced and twisted while arras of ground, overgrown with grass, are swollen, fissured or split and pushed over areas which currently are not subjected to sliding.

Geomorphological examination shows that active fragments occupy the central part of the landslide body and form two distinct strips which, a little down slope of the borehole K1 and K2 transect, merge into one active tongue. This is the tongue which descends to the Ropa channel and is eroded by the river (Figs. 1, 3 and 5). In the Ropa channel, "compression slices" can be observed, especially in winter. The activity of the landslide in the lower part is shown in the marginal zone by open longitudinal cracks with visible slip surfaces. Bulges of fresh colluvium pushed over the stable bedrock provide further evidence of movement. In places, the active fragments of the landslide are adjoined by less active areas where the movement intensity is lower.

Three other zones of considerable activity of the landslide are identified (Fig. 4). The first one occurs west of the discussed area and is formed by a landslide element which is downslope oriented, elongated and slightly bent to SE. The second one has been recognized in the upper part of the landslide system, east of borehole K4. The third, quite large zone occurs east of borehole K1 (Fig. 4).

Based on the detailed borehole logs and natural exposures, a cross-section of the landslide has been devised (Fig. 5). Important elements of this are the slip surfaces, which have been recognized in the cores and — in the later stage of the investigations — by inclinometric measurements. In boreholes K1, K3 and K4 several slip surfaces have been identified. The lowest one occurs at a depth of 28.3 m in borehole K4, and below *ca.* 7.8 m in borehole K3, where it descends below the level of the present-day Ropa channel. The intensity of displacement along individual slip surfaces varies. In the highest borehole, K4, displacement takes place at a depth of 28 m, i.e. at the lowest slip surface, and at a depth of 6–8 m. In borehole K3, the largest displacement increment has been recorded at a depth of 6 m, i.e. just about at the level of the present-day Ropa channel (Fig. 5).

RESULTS

PHYSICAL-MECHANICAL PROPERTIES OF SOIL-ROCK MEDIUM

Based on inspection of the cores obtained from the exploratory boreholes (Figs. 4 and 5) the colluvium composition has been identified using laboratory tests. The core material, sampled in a disturbed state from different depths (between 4 and 26 m), was compact and semi-compact under natural conditions. Cohesive soils and shales predominate in the colluvium. The natural moisture varied from *ca.* 10 to 30%, only exceptionally reaching 40%. A relationship between soil moisture and depth of a given soil type has not been found and probably does not exist. In the cohesive, clayey soils there are intercalations of rock debris. The clay content is high and reaches up to 30% or even more. The soil is treated as loamy aggregate due to the presence of sandstone and shale debris pushed into a soft, plastic matrix.

The liquid limit varies from 30 to 60%. The variability of the plastic limit W_p is smaller: from 18.1 to 21.3%. The low value of plasticity index (0.0–0.25 and *ca*. 0.5, exceptionally) provides evidence of the soil's propensity to flow (viscous behaviour), which can influence the initiation of deformation triggered by rainwater, especially in the subsurface zone. The cohesion and angle of internal friction, which describe the shear strength, are parameters necessary for numerical simulation of the deformation processes. In this case study, these parameters show a high variability, although the same (macroscopically) soil type is analysed: maximum cohesion $c = 2 \div 190$ kPa, maximum angle of internal friction $\varphi = 2.9 \div 20.6^o$, while the averages are 64 kPa and 15.2^o, respectively. Residual c and φ values are approximately equal to the maximum ones.

The above results are strongly biased by sampling locations, and so cannot satisfactorily represent the whole slope massif. Moreover, the structure of the sampled material was disturbed during a core taking as well as during earlier deformation of the colluvium. The reliability of the parameters is also limited due to the testing technique applied (direct shear of a small specimen $6 \times 6 \times 2 \div 4$ cm in a shear box apparatus) as well as due to the presence of sandstone debris. Thus, these parameters do not satisfactorily represent the slope massif and in further analysis they were considered only as qualitative information, describing the soil type or used in the first trials of numerical calculations.

HYDROMETEORLOGICAL CONDITIONS DURING THE STUDY PERIOD

Rainfall is generally recognized to be an important factor when considering slope stability.

The literature provides the "threshold values" determining the limits of rainfall totals and rainfall intensity which, if reached or exceeded, activate mass movements (e.g., Caine, 1980; Govi and Sorzana, 1980; Glade, 1998, 2000; Crozier, 1999; Hennrich, 2000; Zezere and Rodrigues, 2002). In relation to particular regions of the Polish Flysch Carpathians, the threshold values were given by e.g., Thiel (1989), Gil (1997), Rączkowski and Mrozek (2002), Gorczyca (2004), and Gil and Długosz (2006). In such a framework, analysis of water conditions of an individual slope, where various sliding processes might occur, is usually either omitted or treated very superficially.

The case study undertaken attempts to relate hydrometeorological situations to actual water conditions observed in the field on the slope examined and relative to the corresponding displacements. The study period covered only 3 years; it is believed that an extended period of examination might significantly improve the reliability of the findings obtained.

The hydrometeorological records collected by the Research Station IGSO PAS at Szymbark showed that mean annual precipitation during 36 years (1968–2003) was 815 mm. Precipitation lower than the mean was recorded in 1982 (535 mm), but in 1984 the mean annual precipitation (603 mm) was almost the same as in 2003 (614 mm). Curves of cumulative precipitation totals of 2001–2003 compared with those of 1968–2003 indicate that precipitation was close to the average in 2002 while it was much lower in 2003 (Fig. 6).

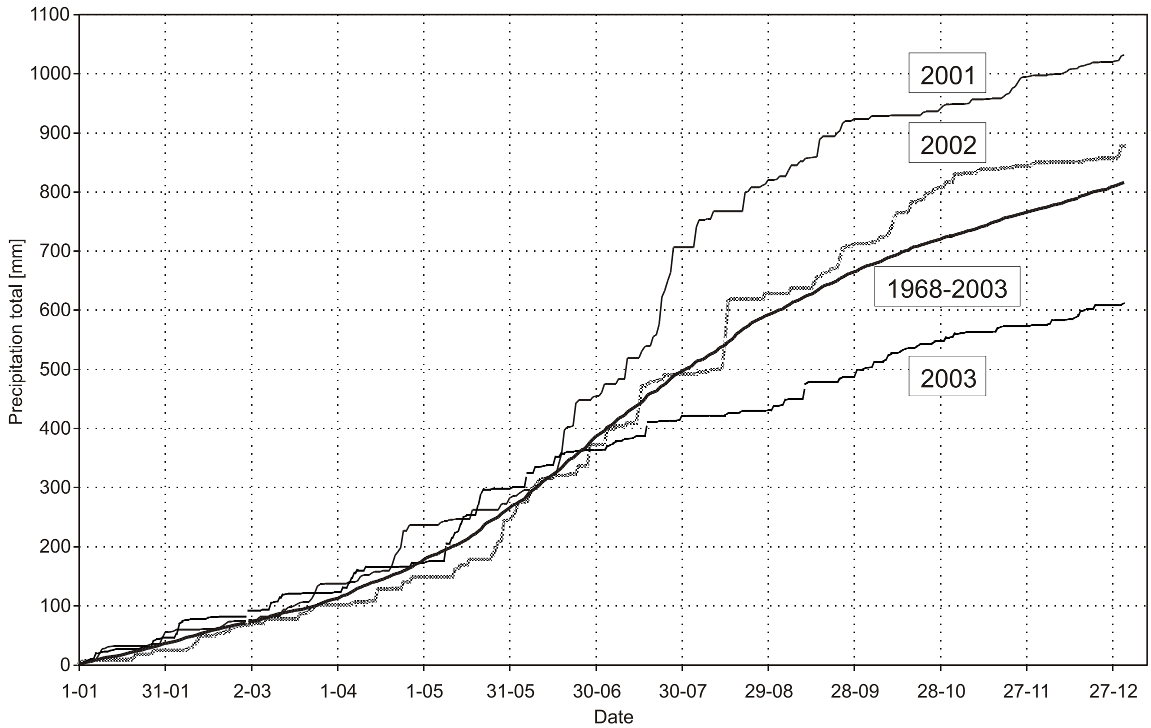

Fig. 6. Cumulative precipitation at Research Station IGSO PAS in Szymbark

Water conditions in the slope massif were determined based on the groundwater level (GWL) measured in Casagrande piezometers, located at a depth of 4–5 m in various parts of the landslide studied (Fig. 4). The collected records refer to the level of the shallow groundwater table.

Based on the curves of groundwater level fluctuations two periods can be distinguished (Fig. 7). In the first one — from autumn 2001 to spring 2003 — the span of the observed fluctuations in ground water level (GWL) varies in a certain range. The second period — from the spring (April–May) to the end of 2003 — is characterized by a deepening of the GWL. This reflects water supply in the second half of 2003 being reduced due to drought, as can be seen in Figure 6. On the other hand, it should not be forgotten that under temperate climatic conditions, meltwater recharge as well as rainfall affects soil saturation. In fact, in the first period distinguished, the GWL rises rapidly during thawing seasons, and then descends relatively slowly (depicted in Fig. 7). The rate of GWL decrease depends on atmospheric conditions succeeding its rapid rise, thus the general lowering trend can be modified by superimposed short-term fluctuations related to changes in water supply due to e.g. inflow of additional rain or meltwater. The field studies performed have shown that the depth and range of GWL fluctuations correlate weakly between particular piezometers, although the latter are located not far apart. This demonstrates the heterogeneity of the geological medium yet partial effects of the terrain morphology cannot disregarded.

DISPLACEMENTS OF THE LANDSLIDE SLOPE STUDIED

Results of displacement measurements are illustrated by the curves showing the position of the borehole axis with respect to its initial position (so called "zero reading" or "reference reading"). The cumulative curves do not always provide clear information on the location of a slide surface (or a slide zone) and the magnitude of displacement; therefore, they are accompanied by the curves of incremental displacement.

During the study period, the movement in the colluvium material occurred mainly at small depths in boreholes K1 (*ca*. 2 m), K2 (1.5–2 m), K3 (6 m) and K4 (6–8 m). Deeper, minor deformations were recorded only in borehole K1 (at a depth of *ca*. 10 m) and in K4 (at *ca*. 28 m). The largest movements, equal to *ca*. 50 mm/year, were recorded in the lower part of the landslide in borehole K3 (Fig. 8). The records of the underground deformation confirm the surface movement registered by geodetic methods, both by the precise GPS (own research) and in the earlier use of classic techniques (Dauksza and Kotarba, 1973). It should be emphasised that horizontal displacements of certain benchmarks situated on the landslide tongue close to the river, recorded in 1968–1971, were as large as 5 metres (Dauksza and Kotarba, 1973). At present, such large displacements are not observed, and according to Cruden and Varnes velocity scale (Cruden and Varnes, 1996), the process is "very slow" (between 1.5 m/year and 60 mm/year) or even "extremely slow", i.e. below 60 mm/year.

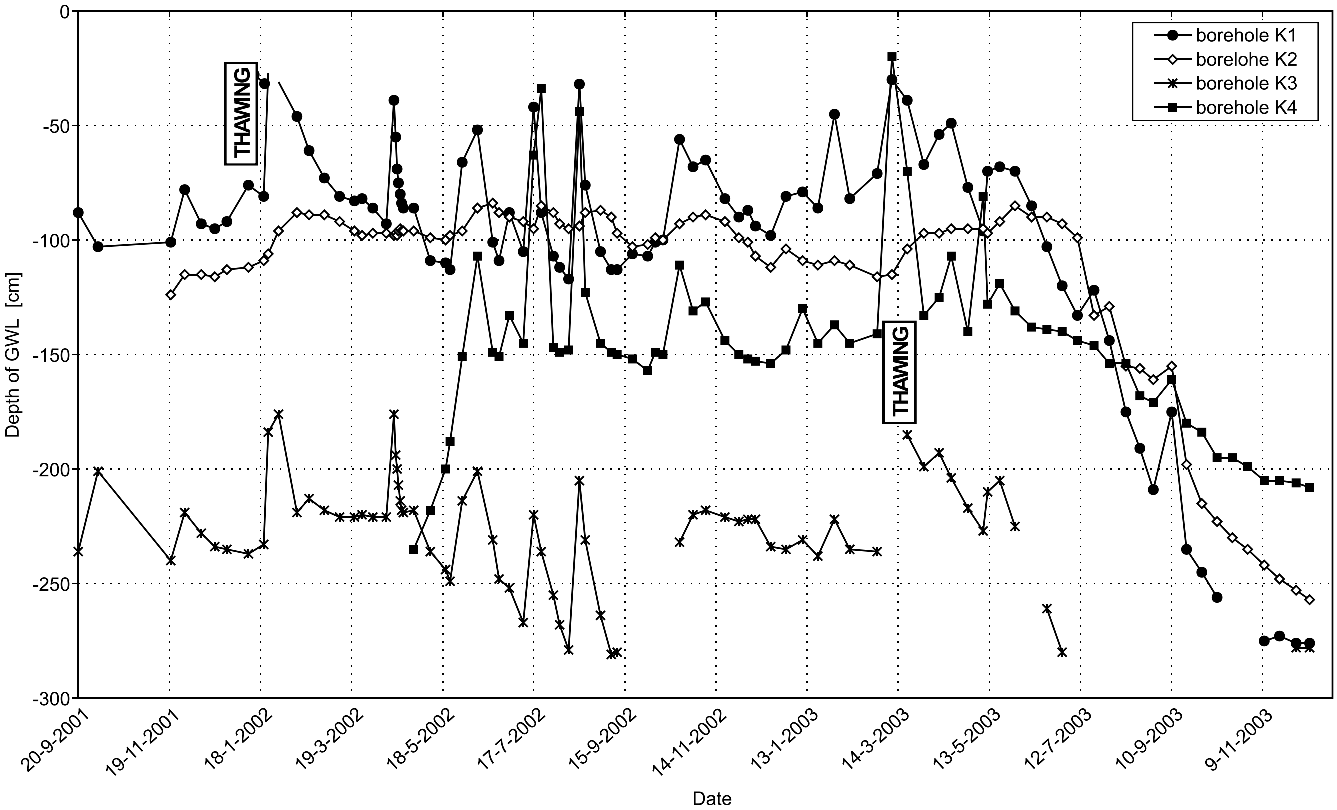

Fig. 7. Groundwater level measured in piezometers

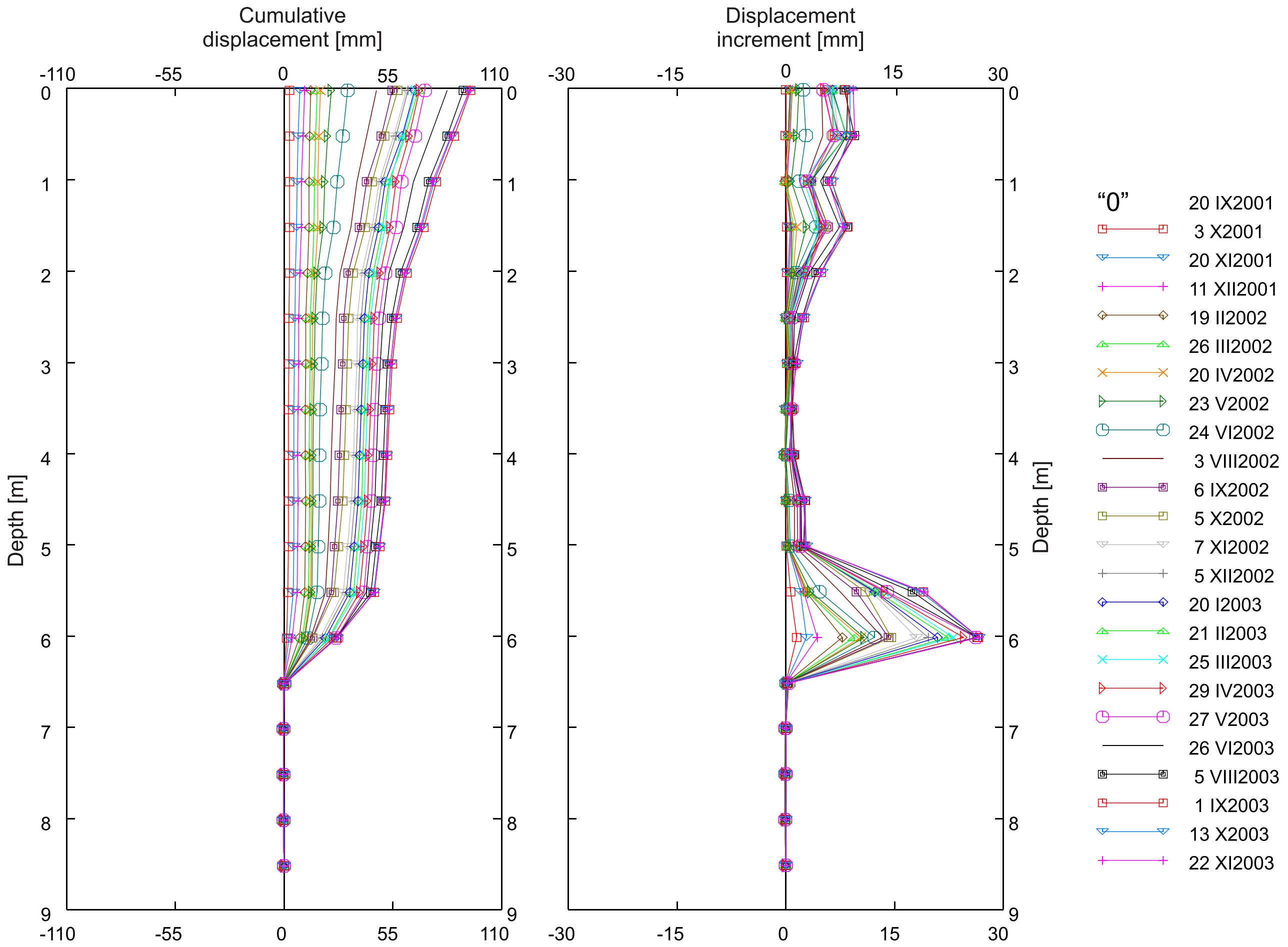

Fig. 8. Cumulative and incremental displacement measured by inclinometer in borehole K3

The results of GPS measurements taken in 2001–2002, and at some locations in 2001–2003, show a significant differentiation of superficial displacements, yet the largest displacements varied from 47 to 617 mm only and were observed on the landslide tongue near to the river.

The inclinometer measurements, apart from showing the deformation zones, allow the analysis of displacements *versus* time. The results have been smoothened using 6-order polynomial and by the curve depicting the moving average with a step = 2. The above approximation reveals a seasonal pattern of the slope deformation. The rate of displacement increases in late spring and/or in summer. In the case of borehole K3 the maximum was in August in the first year of recording (2002) while in the second year (2003) it was in June (Fig. 9). A similar pattern has been observed in other boreholes, although the seasonal differentiation of the displacement rate is not so pronounced. The displacement processes in all the boreholes are similar as indicated by the correlation coefficients larger than 0.95 calculated for the relationships between them. The differences observed show that the downslope section of the landslide body "runs away" from its upper parts.

RELATIONSHIPS BETWEEN PRECIPITATION, GROUNDWATER LEVEL AND DISPLACEMENTS — DISCUSSION

INFLUENCE OF PRECIPITATION ON GROUNDWATER LEVEL

Changes in water level in the landslide colluvium in response to precipitation are complex and difficult to present in the form of a function. As shown above, local fluctuations are imposed on a general descending or rising trend in groundwater level (GWL). These local variations depend on water supply and recharge lag, which are related to environmental condi-

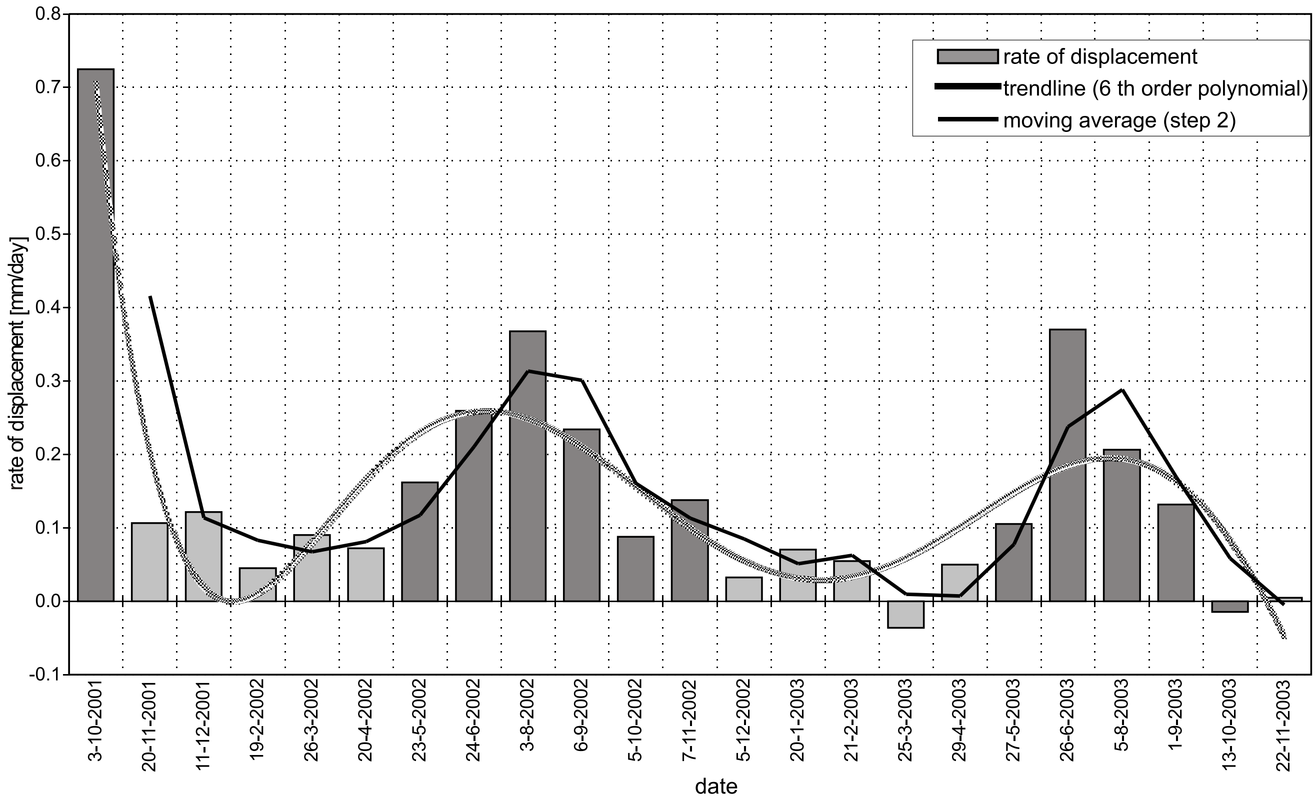

Fig. 9. Displacement rate in borehole K3

Location of borehole in Figure 4; darker bars refer to periods between autumn and early spring

tions. Bearing in mind the complexity of the problem, an attempt was made to find the quantitative relationship between precipitation and groundwater level.

If the winter season is disregarded (i.e. from 1 December 2002 to 31 March 2003), then the relation linking the changes in GWL between particular measurements (i.e. ΔGWL) and the precipitation total during "*i*" days, antecedent to the GWL measurement date, can be expressed by an empirical formula:

$$\Delta\mathrm{GWL} = \beta \cdot D_O + \sum_{i=1}^{i=10}\left(D_{(-i)} \cdot \alpha^{\iota-1}\right) \qquad [1]$$

where: D_o — precipitation total at the measurement date; $D_{(-i)}$ — precipitation total at the day antecedent to the measurement date by "*i*" days; coefficients: β = 0.05 and α = 0.53

It has been stated that the weighted sum of precipitation of 10 antecedent days has the most significant influence on the GWL.

RELATION BETWEEN GWL AND DISPLACEMENT IN BOREHOLES

The change, especially the rise, in the groundwater level does not transform directly into intensification of the landsliding process, i.e. into an increment of displacement rate. Results of the measurements in borehole K3 just indicate that the deeper the groundwater level is, the larger is the displacement (Fig. 10). In other boreholes, the GWL fluctuations do not result in slope displacements. Therefore, another variable, I(GWL_{cumul}) called "cumulated intensity of GWL fluctuations" (Zabuski *et al*., 2004), which would relate the groundwater level to displacement, has been sought. It is expressed by the formula:

$$\Delta(\mathrm{GWL}_{\mathrm{cumul}}) = \sum_{k=2}^{k=i}\left(\left|\mathrm{GWL}_k - \mathrm{GWL}_{k-1}\right|\right) \qquad [2]$$

It is the sum of all absolute values of the groundwater level fluctuations between subsequent measurements (disregarding whether it is a fall or a rise) from the onset of measurements to the last record with index "*i*". GWL_k denotes the groundwater level in the *k*-th measurement.

Figure 11 presents the relationship between I(GWL_{cumul}) and horizontal displacements in boreholes K1 and K3. High values of correlation coefficients "*r*" confirm the appropriateness of the introduced variable (significance level for both cases is $p << 0.05$).

The reasoning which clarifies the relationship between horizontal displacement and intensity of groundwater fluctuations is based on the hypothesis that within the range of GWL fluctuations the soil is subjected to alternating wetting and "drying" or at least its moisture varies to a great extent. In consequence, the physical processes taking place in the soil lead to its weakening (worsening of strength properties). This weakened zone coincides with a slide zone, so intensified deformation takes place.

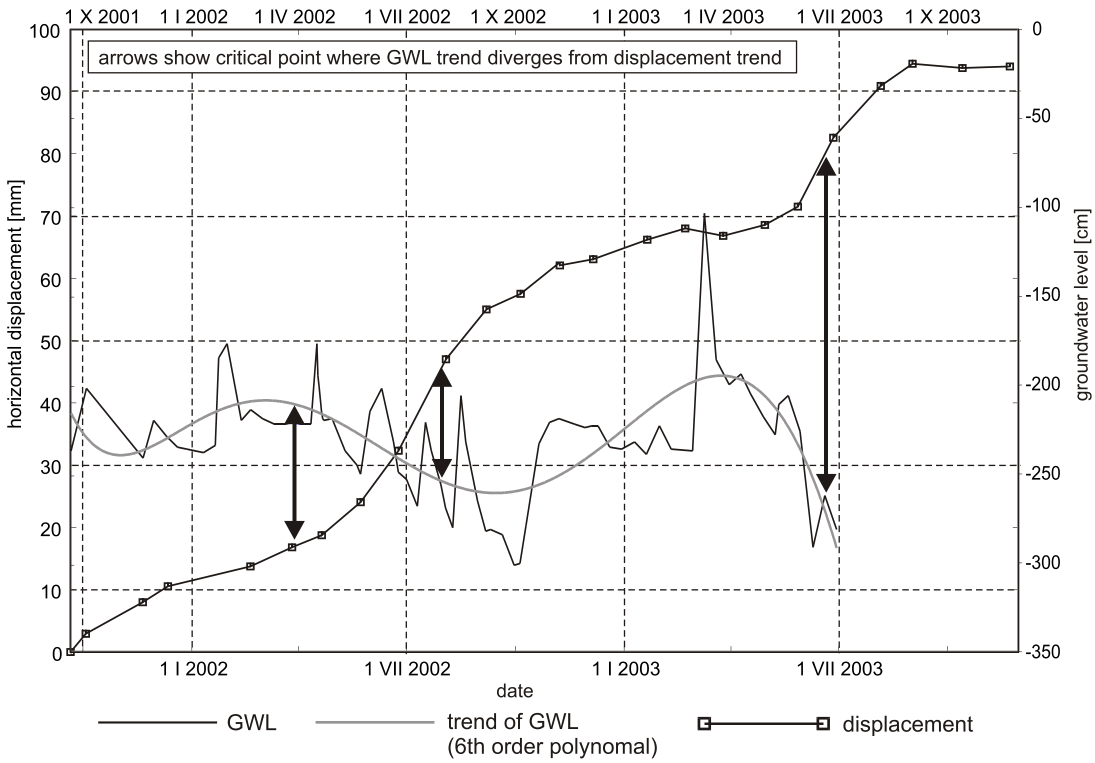

Fig. 10. Groundwater level and horizontal displacement in borehole K3

Location of borehole in Figure 4

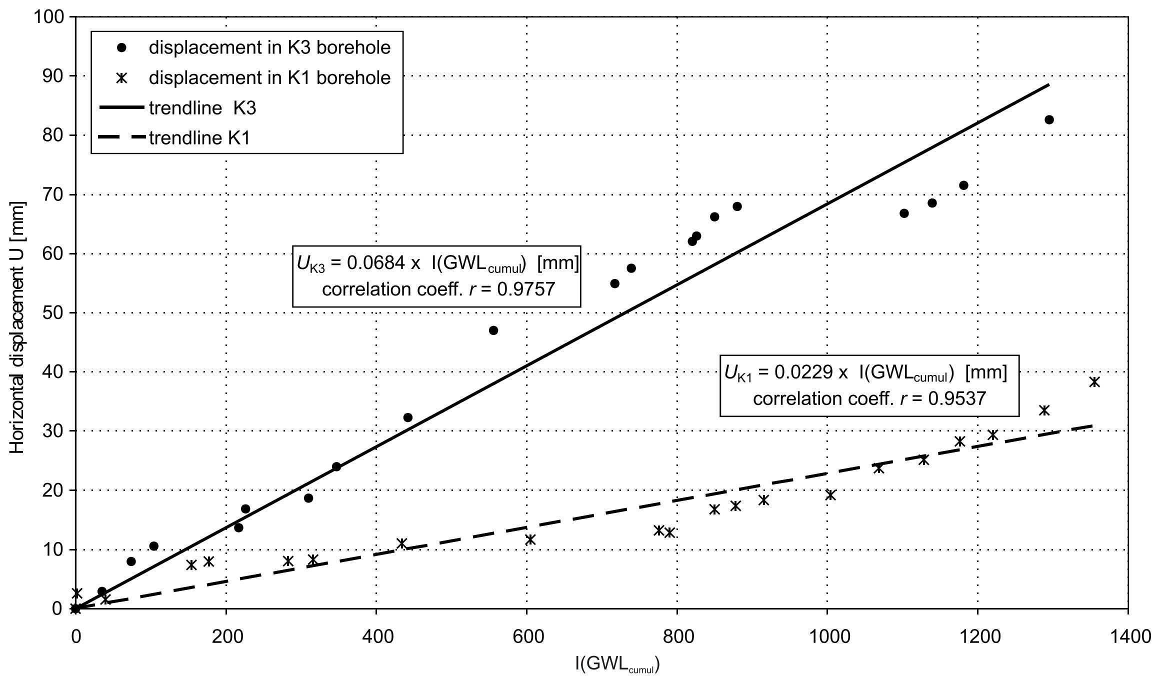

Fig. 11. Cumulative intensity of groundwater fluctuations versus horizontal displacement of K1 and K3 borehole, with regression formula and correlation coefficients

I(GWL$_{cumul}$) — cumulated intensity of GWL fluctuations (cm); location of boreholes in Figure 4

NUMERICAL ANALYSIS OF THE SLOPE DEFORMATION PROCESS

The numerical analysis aims at calculation of the stress distribution and at simulation of slope deformation. Simulation results refer to the profile running from the highest point of the landslide to the river level, and are calibrated using measured displacement data.

The numerical model has been divided into finite difference zones (Fig. 12A). Due to the lack of appropriate data, a hydrostatic stress field was assumed. As the most unfavourable hydrological conditions have been taken into account, the ground water level is assumed to coincide with the terrain surface. The calculations in the first stage have been preformed using the lowest values of the strength parameters, obtained from the geotechnical analysis, and elasto-ideally plastic behaviour of the medium was assumed. The results showed that even with such low parameters the slope is stable, which is obviously in contradiction to the behaviour observed in nature. Moreover, the results do not take into account changes in time, so do not reflect the real behaviour of the slope. Because of that, a rheological model of the medium has been worked out which allows simulation the creep process. The model parameters were altered and modified in a trial-and-error procedure and finally an agreement between the calculation results and the displacements was recorded. In such an approach goodness of model parameter fitting is tested on the basis of agreement between measurements and calculation results.

In order to consider slope displacement in time, a visco-elastic-ideally plastic behaviour of the medium is assumed. The visco-elastic behaviour corresponds to Burger's model, which consists of Kelvin and Maxwell segments, composed of spring and dashpot, while the ideally plastic behaviour, where the values of maximum and residual strength parameters are identical, corresponds to the well-known modified Coulomb-Mohr criterion. The details of these models are described in many papers and textbooks (e.g., Jaeger, 1969; Langer, 1979; Derski *et al*., 1982; Dusseault and Fordham, 1993; Zabuski, 2004; Marcato *et al*., 2008), thus a thorough description.

The model of the slope consists of layers, the parameters of which are listed in Table 1, while the layer arrangement is shown in Figure 12B using cohesion as an example. The parameters given in the table, when implemented to the model, allow the obtaining of simulation results that agree with the displacements and the depth of the slide zone observed in the field. The set of parameters can be considered as appropriately assigned, if such agreement is reached. Figure 13 presents a numerical simulation of horizontal displacement after 2-years. Displacement curves obtained from the 2-year long measurements in boreholes K1 and K3 and the corresponding displacement curves from calculations are shown in Figure 14. The conformity of calculations with the measurement results is satisfactory if the complexity of the object is taken into account. The agreement between displacements obtained from simulation and measurements shows the appropriateness both the layer arrangement (see Fig. 12B) and the parameter values (see Table 1). In other words, the results from numerical simulation are supported by the results from measurements.

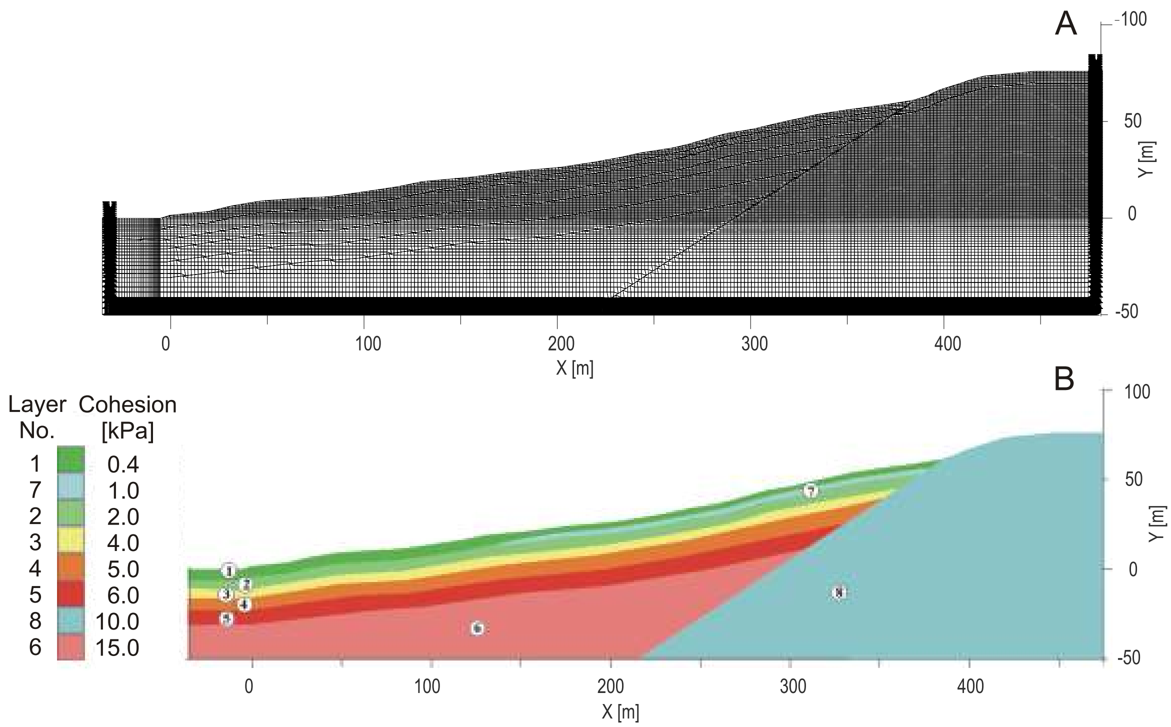

Fig. 12. Numerical model of the Kawiory landslide system

A — finite difference mesh; **B** — arrangement of layers based on geomechanical parameters — cohesion distribution shown as an example

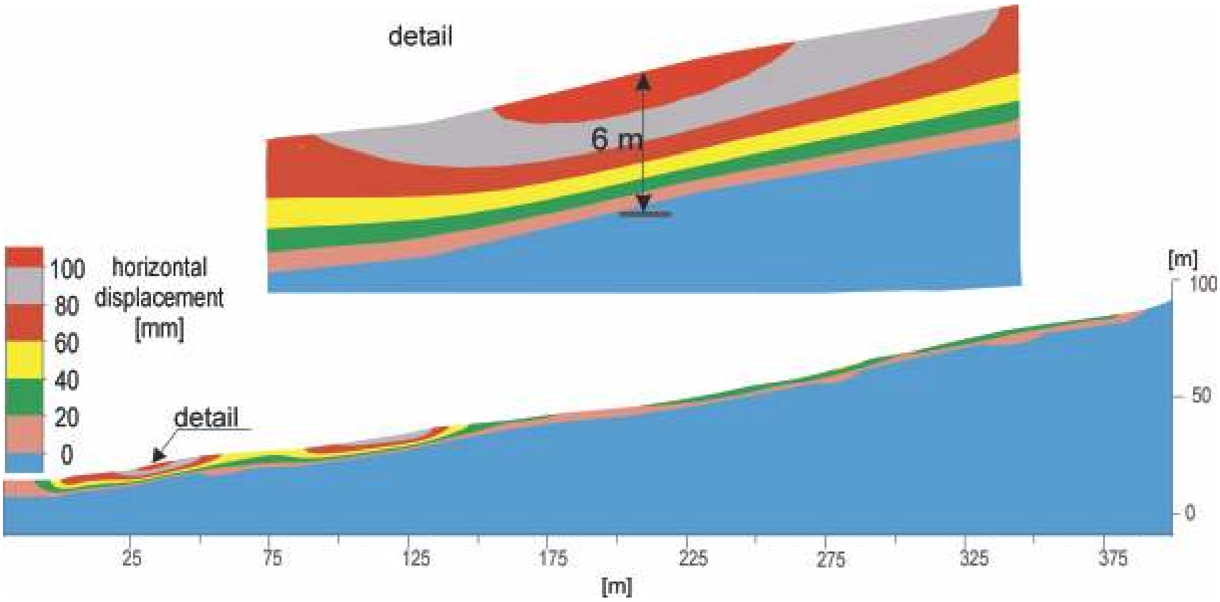

Fig. 13. Field of horizontal displacement after 2 years creep

Table 1

Geomechanical parameters of layers in the slope model

Layer No.	Cohesion c [kPa]	Angle of friction ϕ [°]	Tension strength σ_t [kPa]	Dilation angle ψ [°]	Maxwell's shear modulus G_M [kPa]	Maxwell's bulk modulus K_M [kPa]	Kelvin's shear modulus G_K [kPa]	Maxwell's viscosity coefficient η_M [kPa s]	Kelvin's viscosity coefficient η_K [kPa s]
1	0.4	9	0.2	2.25	7.7	16.67	5	4×10^7	4×10^7
2	2.0	15	1.0	3.75	65.4	141.7	1×10^3	1×10^{14}	1×10^{12}
3	4.0	20	2.0	5.0			1×10^3	5×10^{14}	5×10^{12}
4	5.0	25	2.5	6.25			1×10^4	1×10^{15}	1×10^{13}
5	6.0	30	3.0	7.5			5×10^4	5×10^{15}	5×10^{13}
6	15.0	35	7.5	8.75			1×10^6	1×10^{27}	1×10^{27}
7	1.0	10	0.5	2.5			1×10^3	5×10^{13}	5×10^{11}
8	10.0	32	5.0	8			1×10^6	1×10^{22}	1×10^{22}

Layers 6 and 8 — bedrock (stable); see Figure 12B

CONCLUDING REMARKS

The study performed can be called interdisciplinary as the authors have attempted to combine earth science and engineering approaches to analyse, describe and explain the landsliding process.

Although geological interpretation of the borehole logs pointed to multiple slip surfaces with the major one being deep, the inclinometer monitoring carried out for almost 3 years indicated more significant displacements at lower depths in a relatively shallow subsurface layer (2–6 m deep) of loam and clay deposits. Based on both numerical modelling and inclinometer data the slow movement of the landslide system examined seems to occur almost continually, having a creeping character. Similar processes have also been registered in other parts of the Carpathians, for example in Slovakia (Wagner and Pauditš, 2002). These authors describe the landslide near Liptovsky Mikulas, which shows permanent creep. It provides evidence that such a deformational mechanism can be treated as typical of other Carpathian Flysch slopes.

The onset of slide acceleration depends on the timing of the "wettest" periods. This study has shown that water recharge is often controlled not exclusively by precipitation but by meltwater or by a combined effect of the both. This is why the onset of sliding may be observed in the Polish Carpathians in early spring (March–April). In this way, regional climatic conditions affect the timing of movement acceleration. For example, the

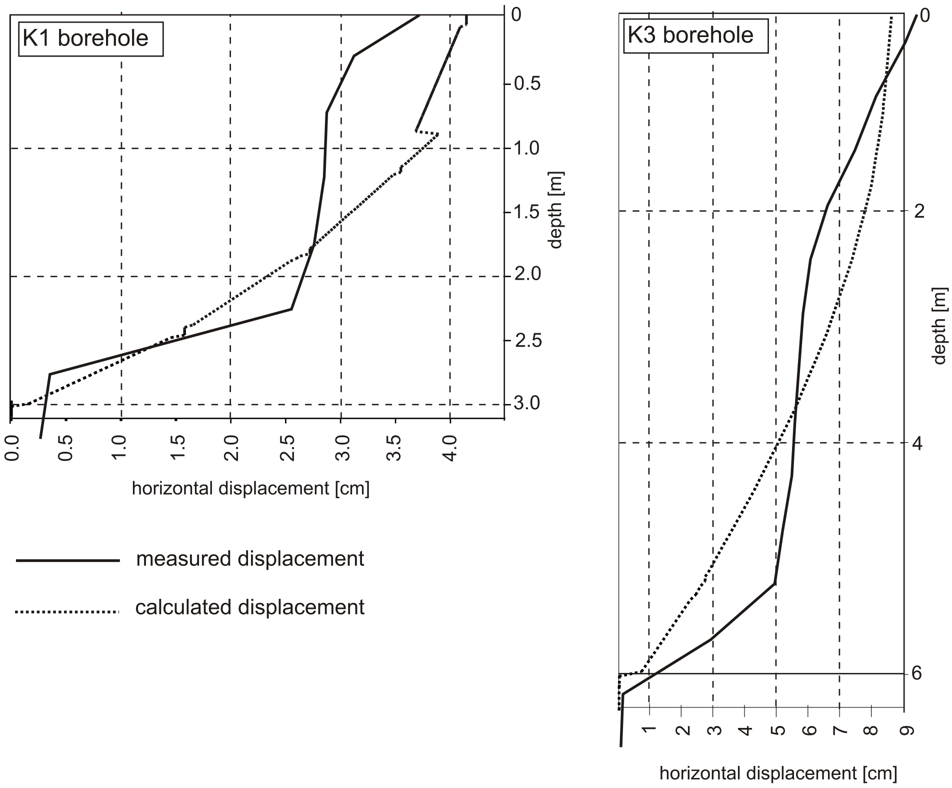

Fig. 14. Comparison of measured and calculated horizontal displacement in boreholes K1 and K3

Location of boreholes in Figure 3

landslides in the Apennines revealing creep mechanism are activated in the late autumn or in winter (Lollino *et al*., 2006; Foglino *et al*., 2006; Tommasi *et al*., 2006). The timing in the Alpine region is not so clearly determined, although two periods of creep acceleration of the landslides on slopes built of flysch or flysch-like massive deposits can be distinguished, namely late autumn–winter and spring, after snow melt (Borgatti *et al*., 2007; Van Asch, 2007). Many slopes in the Alps move monotonously, independently of seasonal atmospheric changes (Marcato *et al*., 2008; Supper *et al*., 2008).

Many papers have demonstrated that landslide movement is associated with water saturation of the medium (i.a. Malet *et al*., 2005; Lollino *et al*., 2006; Tommasi *et al*., 2006), which is usually reflected in groundwater level. The results presented here show that apart from the groundwater depth the intensity of landslide movement is related to the intensity of groundwater level fluctuations. It is likely that the process of frequent groundwater changes in the zone of weak soil causes alternating wetting and drying. This leads to weakening of the mass strength properties.

In order to describe quantitatively the slope deformation process, it is necessary to use advanced numerical models in which rheological processes are considered. The model presented in this paper allowed simulation of the slope displacements during the research. Similar, calibrated numerical models can also serve to approximate estimation of future landslide movements, provided that the external conditions (which could alter the model parameters) do not change significantly. In such an approach, future displacement from simulation and from field measurements can be compared and — in case of disagreement — parameters of the numerical model can be modified. This means that in such an approach the model can be calibrated many times, depending on new results of measurements. The major problem here is lack of data on the viscosity of the medium. In effect, the only acceptable method of simulation is by back analysis (trial-and-error strategy), followed by the comparison of the calculation results with the measured records. Results of numerical simulation show that (in the study period), deformation prevailed in the lower part of the slope; the deformation zones did not concentrate to form a large individual slide, but comprised a series of smaller slides.

Summarizing, it has to be pointed out that the explanation of landslide development and prediction of its future behaviour as well as of an approximate time span to the final stabilization of the movements is possible when an interdisciplinary approach is used. However, each theoretical (here geomechanical and numerical) model has to be strictly formulated and calibrated with the help of the results from methods used in the Earth sciences. The considerations presented show the possibilities and limitations of this approach. They also show the beneficial effects of combining the research of specialists from different domains of science.

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