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Archives of Hydro-Engineering and Environmental Mechanics
Vol. 65 (2018), No. 1, pp. 3–10
DOI: 10.1515/heem-2018-0001
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Analysis of Slope Creep in the Example of a Landslide Slope in Koronowo near Bydgoszcz

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(Received November 20, 2017; revised March 15, 2018)

Abstract

This paper presents the results of a numerical simulation of a slope deformation process. The landslide slope "Grabina" in Koronowo near Bydgoszcz (Poland) serves as an example. A slope profile located in the central part of the slope, between the main scarp and the toe of the landslide, was selected. The average dip of the slope is about 10°, and its length is approximately 55 m.

Elasticity, plasticity and viscosity properties were taken into account in the model of the soil mass that composes the slope. The visco-elastic properties are described by the Burgers model (Mainardi and Spada 2011), and the plastic ones by the Coulomb-Mohr law. A numerical simulation was carried out by the computer code FLAC2D in the plane strain state with the assumption of the Lagrange routine. The model was discretized taking into account the results of inclinometric measurements, which proved that the slide movement was concentrated in a narrow loam zone of 0.5–1.0 m thickness.

No tests of the viscosity parameters were performed, so they were determined by the back analysis and a trial and error method. The calculation results were verified by comparison with the displacement measured by the inclinometric method in three boreholes. The analysis performed demonstrated the possibility of approximating and forecasting landslide displacements by the combined Burgers and Coulomb-Mohr models.

Key words: landslide, creep, inclinometric measurements, Burgers model

1. Introduction

Soil or rock media constituting slopes exhibit viscous properties. Thus the appropriate approach in modelling their behaviour is to consider the creep phenomenon. The elasto-plastic models are improper in modelling continuous or quasi-continuous displacements.

Creep is a deformation process that develops slowly over time under constant load conditions (Jaeger 1969). This phenomenon is described by models in which the medium has properties of a viscous fluid. Out of all rocks, the most viscous is rock salt (Passaris 1979, Tan Tjong Kie 1993). Nevertheless, other types of rock –

even very hard ones (e.g. granite, gneiss) – also possess viscous properties (Ito 1983, 1991, 1993, Langer 1979). Tests of clay shales show that their behaviour also clearly depends on time (Sun and Zhou 1983).

Investigations of soil and rock creep *in situ* and in the laboratory have rarely been performed. This situation may be due to the long duration of creep experiments and the need to employ unique apparatus (Dusseault and Fordham 1993). It results in poor recognition of creep in soils and rocks and scarce information regarding their parameters (Zabuski 2003).

The aim of this paper is to describe the rheological model applied and to estimate its "equivalent" parameters in the case of soils on the experimental slope Grabina-1 in Koronowo near Bydgoszcz (Zabuski et al 2015), see Fig. 1. Because of the lack of creep parameters, a numerical simulation of slope deformations and the procedure of back analysis were employed for their estimation. The results were verified by comparing the displacements computed with those measured by inclinometers. The necessity of the back analysis application results from the fact that in a heterogeneous medium it has been practically impossible to find the viscosity parameters by laboratory tests, and thus the application of back analysis was necessary.

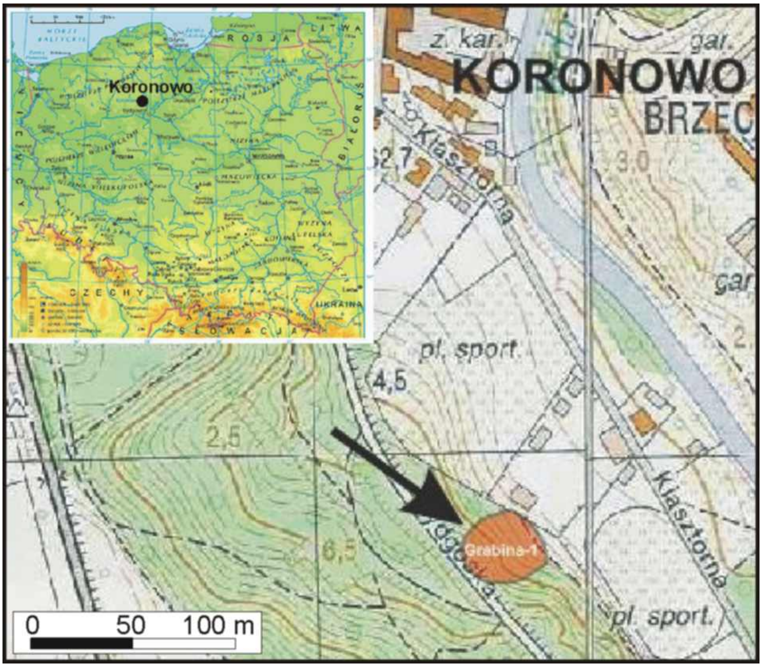


Fig. 1. Location of the landslide slope Grabina-1

2. Modelling of the Creep Process

In response to the deviator of the stress state, the medium behaves as an elasto-visco-plastic body. It is assumed that the strain rate is a sum of visco-elastic and plastic components. A visco-elastic component is described by the Burgers model (consisting of Kelvin's and Maxwell's parts, Fig. 2). The model is composed of springs and pistons arranged in a series (Maxwell's part) and in parallel (Kelvin's part) and is defined by four parameters, namely, Kelvin's and Maxwell's viscosity coefficients, as well as shear and bulk elasticity moduli. Plasticity is described by the modified Coulomb-Mohr criterion with three parameters: cohesion, angle of friction and tension strength.

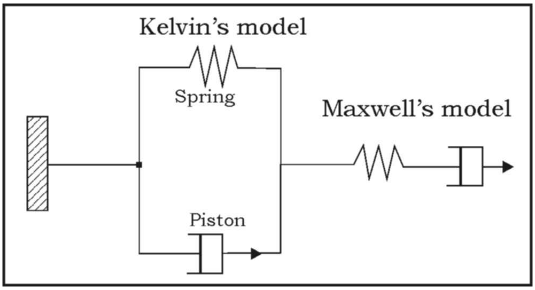


Fig. 2. Burgers visco-elastic model

A serious difficulty is connected with the determination of the viscosity coefficients in the Burgers model. The data in the literature are scarce. The order of magnitude of these coefficients for rock salt is equal to 10^4–10^5 kPa·s, and the moduli of elasticity are in the range from 3×10^7 to 8.5×10^8 kPa (Passaris 1979). The coefficients for granite change in the range from 3.5×10^{19} to 10^{21} kPa·s. According to Sun and Zhou (1983), the elasticity moduli for clay shales are 1.25×10^4–5.4×10^5 kPa, and the viscosity coefficients range from 2.9×10^{14} to 1.2×10^{15} kPa·s. In an analysis of displacements of a rock mass (the so-called "normal" Carpathian flysch, in which the contents of clay shales and sandstones are approximately the same), Kelvin's viscosity coefficient was equal to $\eta^K = 10^{13}$–5×10^{13} kPa·s and Maxwell's $\eta^M = 10^{16}$–10^{20} kPa·s (Zabuski 2003). Data for soils and very weak rock practically do not exist. Therefore, in this paper, a trial-and-error method was used to estimate these parameters by comparing the calculated and measured displacements.

3. Procedure of the Numerical Analysis of Creep

The calculations were performed by the numerical code FLAC 4.0 (Itasca 2000) based on the finite-difference method, under the plane strain conditions (2D), assuming the Lagrange routine (i.e. coordinates of the nodes change in each calculation step). The simulation of the process was divided into two stages. In the first stage, the elasto-plastic behaviour of the medium was assumed. The parameters of elasticity and plasticity were determined by trial and error in such a way that the slope was stable and the safety factor was approximately equal to 1.0 (limit equilibrium state). This is tantamount to the assumption that the deformation process in the second stage, in which visco-elastic behaviour was assumed, developed solely due to creep.

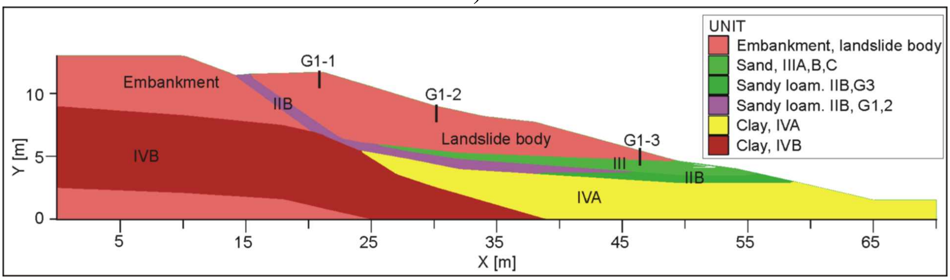
The displacement calculated for a specific period of time was compared with the displacement measured by inclinometers in the same period. Because of the Lagrange routine, the slope geometry changes during its movement, and this can influence the stability conditions of the slope. However, such changes were not observed in the present case, as displacements were very small.

4. Numerical Simulation of Creep on the Experimental Slope "Grabina-1"

The slope profile was located in the central axis of the slope, between the main scarp and the toe of the landslide. The average dip of the slope was about 10°, and the length was approximately 55 m.

The model was discretized taking into account the results of inclinometric measurements, which showed that the slide movement was concentrated in a narrow loam zone of 0.5–1.0 m thickness, and the landslide body above that zone practically did not undergo deformations and could be modelled as elastic. A division of the model into geotechnical layers is shown in Fig. 3, and their parameters – determined by trial and error – are assembled in Table 1.

a)



b)

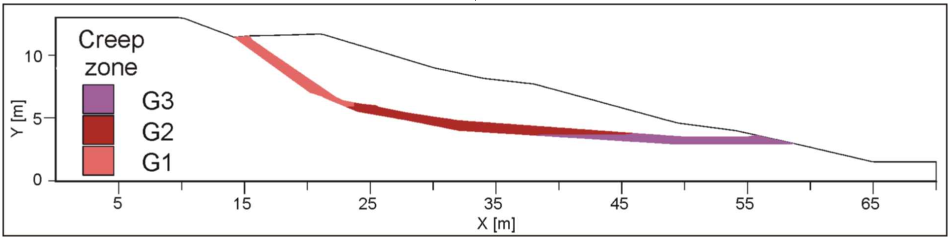


Fig. 3. Model of the Grabina-1 experimental slope; (a) division of the slope into geotechnical units (G1-1,2,3 – inclinometric boreholes); (b) differentiation of the viscosity parameters of soil along the sliding zone

Three inclinometric boreholes were installed on the slope: G1-1 in the region of the main scarp, G1-2 in the central part and G1-3 in the lower part of the slope. The ground water table was measured only in these boreholes (piezometric boreholes were not installed on this slope). There was no water in boreholes G1-1 and G1-2, that is, in the upper and middle parts of the slope. Water in borehole G1-3 was present at a depth of 2.5–3.0 m, that is, below the slip zone. Despite its depth, it could have contributed to soil softening.[1]

Table 1. Geotechnical parameters of the soil units

Zone	Cohesion [kPa]	Friction angle [°]	Maxwell's shear modulus [kPa]	Maxwell's bulk modulus [kPa]	Kelvin's shear modulus [kPa]	Maxwell's viscosity coefficient [kPa s]	Kelvin's viscosity coefficient [kPa s]
Bedrock	100	32	38500	83300			
Layer IIIa	1	27	38500	83300			
Layer IVa	35	5	21154	45833			
Layer IVb	40	5	23077	50000			
Slide lower part (IIb); G3	4	3	38500	83300	5E+4	1.5E+10	1.5E+10
Slide middle and upper part (IIb); G1, G2	8	5	38500	83300	5E+4	1.5E+11	1.5E+11

Figure 4 presents the calculated horizontal displacement field of the slope between January 11, 2010, and September 6, 2016. The curves of the horizontal displacement calculated and measured in borehole G1-2 as a function of depth are drawn in Fig. 5. As it is seen, the differences between displacements obtained by these two methods are not large.

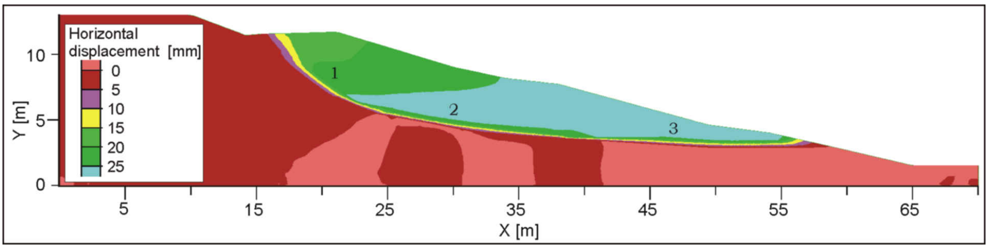


Fig. 4. Field of the calculated horizontal displacements that occurred between January 11, 2010, and September 6, 2016; (1, 2, 3 – points of the recording of horizontal displacement during simulation)

[1] Because to the structure of the inclinometric tubes – which are built of 3 m long sections – the results of water level measurements are problematic.

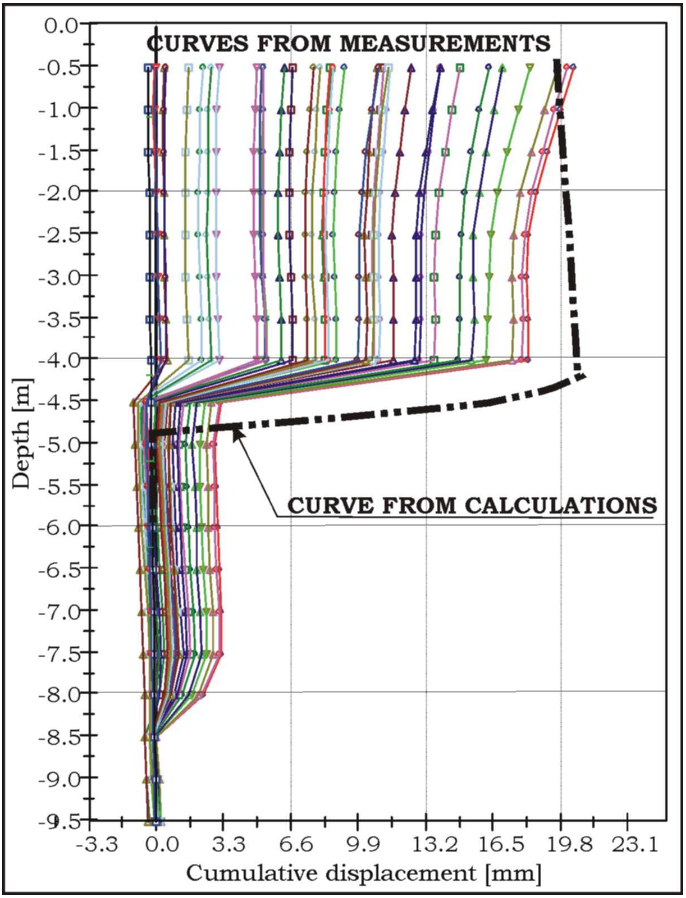


Fig. 5. Curves of the measured and calculated displacements in borehole G1-2

The calculated displacement (Fig. 6, dotted line) increases linearly, whereas the curve of the measured displacement is irregular. Despite these irregularities, the borehole moved monotonously without any seasonal fluctuations. The slip zone in this borehole lays at a depth of 4.5–5.0 m and, moreover, it was ”dry” throughout the whole measurements period. Thermal effects (related to seasonal changes in temperature) were therefore absent and had no influence on the measured displacement. On the other hand, such seasonal changes were very clear in borehole G1-3, although the displacement trend was linear. This can be explained by the shallow depth (2.0–2.5 m) of the slip zone in this borehole. The rate of displacement increased in the spring-summer period and decreased in the autumn-winter period.

5. Summary and Conclusions

In the paper landslide deformation processes were analysed. Numerical calculations of these processes, taking into account the viscous (creep) phenomenon, were

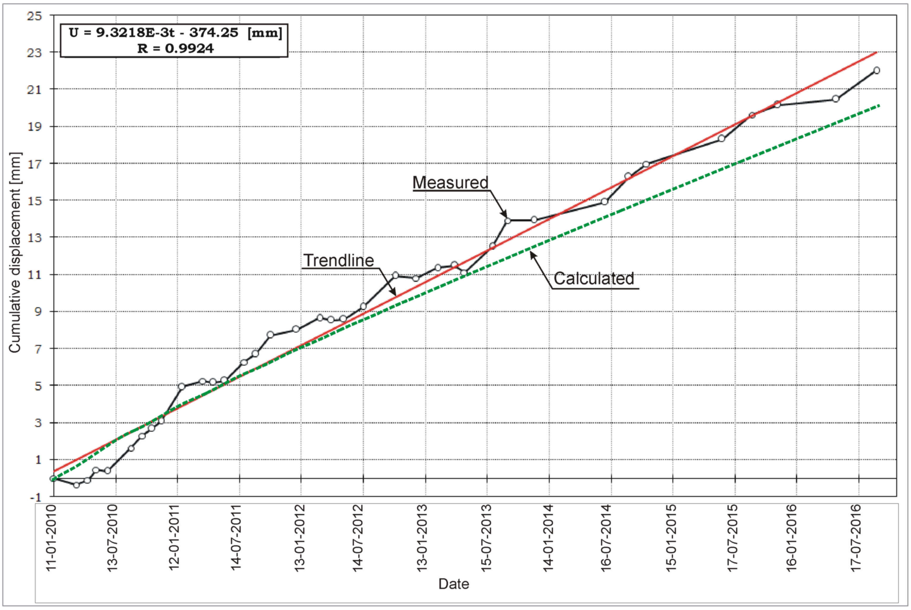


Fig. 6. The horizontal displacements calculated and measured in borehole G1-2 as functions of time

carried out for an experimental landslide slope. The creep behaviour of the slope was described by the Burgers model, whereas its plasticity was modelled by the Coulomb-Mohr law.

The appropriateness and credibility of the simulation results were verified by comparing calculated horizontal displacements with those measured by inclinometers in the boreholes. The back analysis procedure made it possible to estimate the viscosity parameters. The coefficients of viscosity were in the range of $\eta^{K,M} = 1.5 \times 10^{10}$–$1.5 \times 10^{11}$ kPa·s, and the elasticity moduli ranged from 4×10^4 to 5×10^4 kPa.

It was demonstrated that landslide displacements can be approximated and forecasted by the application of the visco-elastic Burger's model combined with the plastic Coulomb-Mohr model. The results of the analysis have proven the effectiveness of this approach; one disadvantage is the lack of the medium's parameters. Future research should determine these parameters in the laboratory, and by applying the back analysis method and numerical modelling.

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