

Rheological investigation for the landslide Slano Blato near Ajdovščina (Slovenia)

Reološke raziskave za plaz Slano Blato pri Ajdovščini

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Abstract

The landslide Slano Blato, is situated above the village Lokavec near Ajdovščina in the west of Slovenia. It has a relatively long history and was first mentioned in a document in 1887. At that time it destroyed a part of a main road and reconstruction works took 17 years. In the last decade, movement of the landslide was observed in November 2000, when it reached distances of 60–100 m/day. By means of geotechnical research work on the landslide in the year 2004, several rheological tests were also carried out, which is not usual for geotechnical research work. A stability analysis was carried out numerically by applying the Burger elasto-plastic model. The model took into account geomechanical and rheological characteristics of the landslide.

Izvleček

Plaz Slano Blato leži nad vasjo Lokavec pri Ajdovščini v zahodnem delu Slovenije. Ima že dokaj dolgo zgodovino, saj je bil v dokumentih omenjen že leta 1887. V tem času je uničil glavno cesto in njegova sanacija je trajala 17 let. V zadnjem desetletju so bili prvi večji premiki na plazu v novembru 2000. Največji izmerjeni pomiki splazele mase so bili 60–100 m/dan. V letu 2004 so se izvajale geotehnične raziskave za namen pridobitve podatkov za sanacijo plazu. V sklopu teh raziskav so bile izvedene tudi obsežne reološke raziskave. Stabilnostne analize so bile izvedene z Burgerjevim elasto-plastičnim modelom. Model pri izračunu upošteva geomehanske in reološke karakteristike splazele mase.

Introduction

Landslide is an important erosion process in Slovenia, affecting 8000 km² of labile or potentially unstable slopes (around 40 % of the country's area) mainly composed of unconsolidated or partially consolidated fine – grained soils (Mikoš et al., 2004).

The Slano Blato landslide is situated in the west of Slovenia (Figure 1), above Lokavec village (Figure 2), on the border between the Alps and the Mediterranean region. Within 100 km of Slano Blato there are three large landslides, each with a potential sliding mass of over 500,000 m³. Also some other relatively large landslides are located in the Slovenian Alps.



Figure 2. The Landslide Slano Blato, above the village Lokavec

Slika 2. Plaz Slano Blato, nad vasjo Lokavec

The Slano Blato landslide has a relatively long history and having been first mentioned in a document in 1887. At that time it destroyed a part of a main road after which reconstruction works took 17 years. More recently, movement of the landslide was observed in November 2000, when it reached peak displacement rates of 60–100 m/day.

The landslide Slano Blato was probably activated, as an earth flow, by a combination of several events. In 1998, a strong earthquake occurred in the Upper Soča River valley (Vidrih, 2001). And next, the year 2000 was very wet and the old drainage system was not maintained any more. Intense rainfalls which cause large landslides are not rare in the Alpine regions of Italy, (Guzzeti, 2004), Switzerland and Austria (Moser, 2002).

Detailed investigation of the landslide was undertaken in the year 2004, to determine the depth of the landslide, its geotechnical and rheological parameters.

The models, which are usually used for the analysis of landslides are the Mohr-Coulomb, the Drucker Prager or the von Mises model.

A numerical stability analysis was performed by applying the finite difference method with Burger visco-plastic model.

The model takes into account the geomechanical and rheological characteristics of the landslide. The model has not been used in geotechnical practice very often. Probably is the reason in the relevant rheological soil parameters for the calculation. For that aim exacting rheological tests have to be done that are not usual tests in the geotechnical investigation work.

The finite element model has already been used for the Val Pola landslide, using the classical elasto-plastic law and quasi static time stepping (Crosta, 2001). The Burger visco-plastic model, which was used in our case, has not been used for the landslide problems yet.

Geology

The Slano Blato landslide is situated at the contact between Triassic limestone and Eocene flysch formation (Figure 3). The Eocene flysch consists of marl and layers of sandstone with thickness of centimetres or several meters. The rock is highly tectonically deformed.

The limestone was overthrust on to the flysch over a very large distance along

the Trnovski overthrust. In consequence the region consists of large synclines and anticlines. The upper part of the limestone is at 670 m above sea level. Limestone is fissured into blocks with dimensions of several cubic meters.

The limestone is overthrust on to the massive sandstone, which belongs to the flysch series. The contact dips at approximately 10° to the NW. Based on the sediment texture, inverse positions of layers were established in the upper part of the landslide. Inverse layers are observed even up to 550 m. Throughout the landslide several faults with dinaritic dip direction $330\text{--}345/55\text{--}75^\circ$ were observed.

The flysch in the region of the landslide can be divided into three parts:

- layers of sandstone of thickness between one and several meters
- a region with alternation of marl and 10 cm thick layers of sandstone
- a region where layers of marl prevail under the layers of sandstone.

The dip direction of layers is WN, which is favourable for slope stability.

The flysch is covered with clayey gravel, that forms the landslide mass. This is very

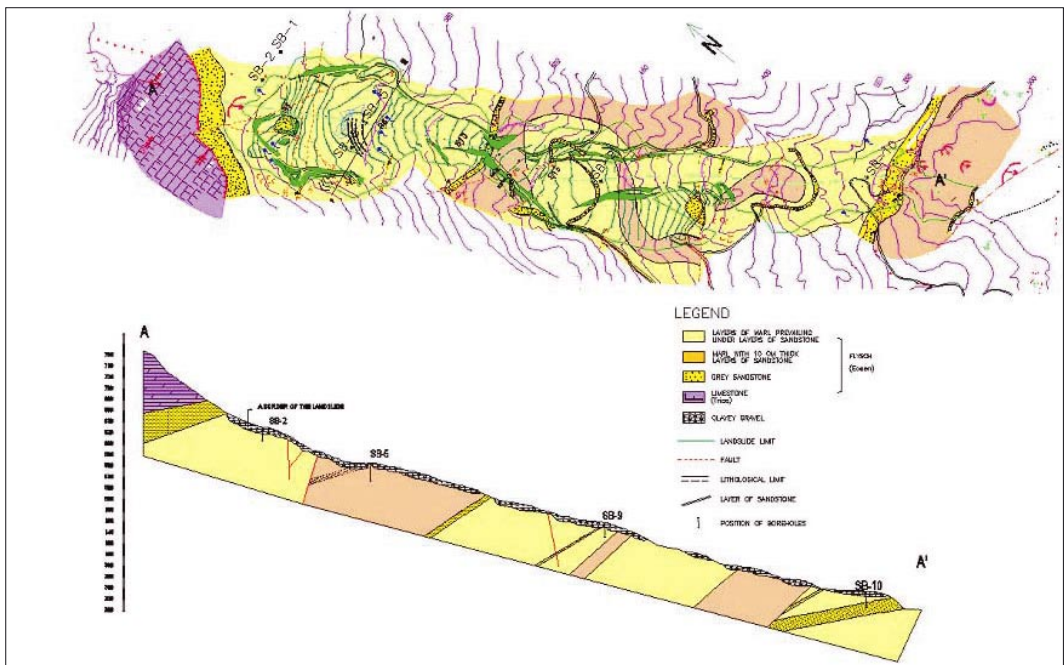


Figure 3. Geological map and profile of the landslide Slano Blato

Slika 3. Geološka karta in profil za plaz Slano Blato

heterogeneous, with blocks of limestone, sandstone and clayey silty gravel. The thickness of the gravel is 3 to 10 m, as ascertained by borehole logging and geophysical investigations.

Field and laboratory measurements

Geomechanical characterisation of the landslide

Geomechanic characterisation of the gravel material and the flysch have been undertaken as follows.

Flysch layers

Logging of the boreholes determined that the RQD index of the flysch is 0. The marl is highly tectonized, in places even into silty grey clay. The intermediate layers of sandstone are also highly fissured. In the laboratory tests the water content (w), liquid limit (w_l), plastic limit (w_p), dry unit weight (γ_{dry}), uniaxial strength (Q_u), angle of friction (ϕ) and cohesion (c) were determined (table 1). The uniaxial strength Q_u proved to be very low. Shear vane test, yielded on intact friction angle of 8.4° , and a residual friction angle of, $\phi_{rez} = 4.4^\circ$. These values are very low.

Table 1. Geomechanical properties of the flysch layers

Tabela 1. Geomehanske lastnosti flišnih plasti

w %	γ_{dry} KN/m ³	Q_u kN/m ²	ϕ °	c KN/m ²
10–14	18–20.6	155–323	22–27	0–37

Landslide gravel material

The results of geotechnical testing of the landslide gravel material proved to be highly depended upon the condition at the take of sampling. Samples collected in dry weather had a much lower water content (around 12 %) and higher strength (Table 2). The sam-

ples that were taken during a rainy period of drilling, on the other hand, had water content of 16–17 % and lower strength. The index of plasticity, I_p , was between 19 and 32 % in keeping with results obtained for Austrian earth flows (Moser, 2002).

Rheological investigations

For rheological tests samples were prepared from sieved landslide materials with particles below 63 μm . This particle fraction represented 36 wt % of the total sieved material, which was proved as the critical part for material sliding. Samples of different water contents, from 35 to 60 %, were prepared by adding water to dry powders. Samples were taken from the surface and at a depth of 8 m at different locations of the upper part of the landslide. In order to allow complete wetting of the particles, rheological tests were performed two days after the preparation.

The rheological tests were carried out using the controlled stress rheometer, Haake RheoStress RS 150, equipped with a parallel plates sensor geometry (with serrated surface), PP 25, of 1.2 mm gap. The measurements were carried out under destructive and non destructive shear conditions at 23 °C. A small amount of water, placed around the measuring sensor and covered by a solvent trap, was necessary to prevent water evaporation from the samples. Due to the peculiar behaviour of the investigated semi-solid samples, measuring protocols were predetermined in order to obtain repeatable experimental data. Shear stress was increased for 3 minutes under destructive shear conditions. The shear stress ranges, which depended on the amount of water in the sample, were selected in the range where the transition from creep flow to shear flow was expected.

The viscoelastic properties of samples were examined under non-destructive conditions of oscillatory shear and by creep-recovery tests. The upper limit of the linear viscoelastic response (LVR) was determined

Table 2. Main geomechanical properties of sliding mass

Tabela 2. Geomehanske lastnosti splazele mase

Properties	w %	w_p %	w_l %	γ_{dry} KN/m ³	Q_u kN/m ²	E MPa	ϕ °	c KN/m ²
Boring in dry period	12	21	52	19.6–20.3	7	29	15	
Boring in wet period	16–25.6	20.4	50	15.2–15.6	64–125	4	24	18

	$w = 50\%$	$w = 40\%$
G_M – Maxwell, (Pa)	1.92E + 05	1.11E + 06
η_M Maxwell, (Pa.s)	1.95E + 07	1.30E + 09
η_K (Kelvin Voight), (Pa.s)	2.14E + 06	5.02E + 06
G_K (Kelvin Voight) (Pa)	5.92E + 04	1.53E + 05

Table 3. The material properties, the elastic modulus $G_{M,K}$ and the viscosities, $\eta_{M,K}$, evaluated as parameters of the Burger model for sample 405 at water content of 40 % and 50 %

Tabela 3. Reološke lastnosti, elastični modul $G_{M,K}$ viskoznost, $\eta_{M,K}$, kot parametri Burgerjevega modela za vzorec 405 pri vsebnosti vlage 40 % in 50 %

from stress sweep tests under oscillatory shear conditions. The mechanical spectra of the examined suspensions were evaluated by applying frequency sweep experiments in the LVR. Creep-recovery tests were performed by applying a constant shear stress for 5 min and measuring the increased shear deformation in the sample during creep and recovery.

By increasing the shear stress during the rheological tests under destructive shear conditions the material deformed (creep flow) and in narrow shear stress range the viscosity drastically dropped, as shown in Figure 4. Due to high solid loadings and the nature of the samples, a homogeneous shear flow field was not achieved. Critical shear stress, at which the transition from creep flow to shear flow occurred, was determined for samples with different contents of water. Viscosities of the samples at different water contents were taken from the plateau region of the creep flow. As shown in Figure 5, the critical shear stress and the viscosity strongly decreased with increased water content in the investigated samples, independently of

sample location in the landslide. From rheological tests and from the geomechanical characterisation of the examined landslide materials it was concluded that the critical water content for the formation of earth flow could be about 40 %.

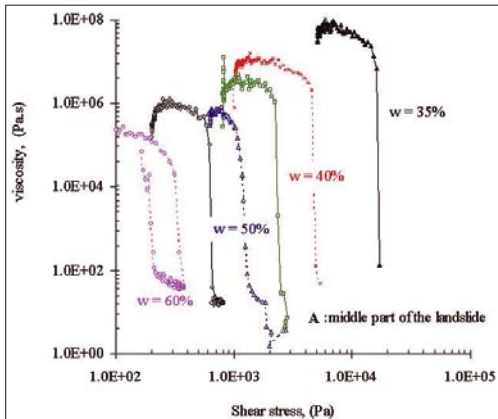


Figure 4. Determination of critical shear stress from stress sweep tests for the sample from middle part of the landslide contained different water content, from 35 % to 60 %

Slika 4. Določitev kritične strižne trdnosti iz reološke preiskave za vzorec iz osrednjega dela plazju, pri vsebnosti vlage med 30 in 60 %

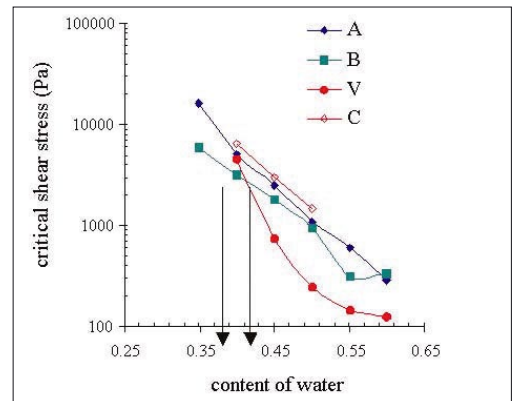
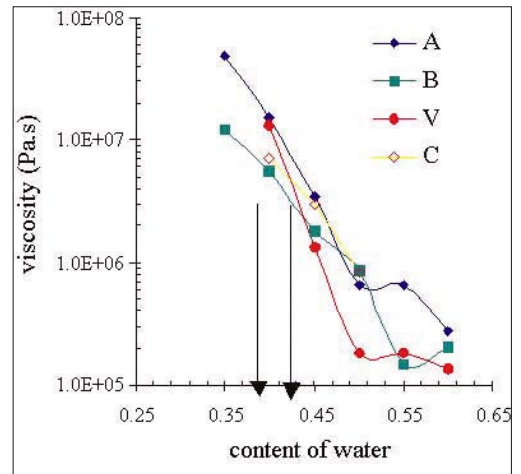


Figure 5. Influence of water content on critical shear stress and viscosity of examined samples taken from different regions of the landslide: A: middle part, B: from borehole of the upper part, C: upper part – at the same location as B, D: upper part

Slika 5. Vpliv vlage na kritično strižno trdnost preiskanih vzorcev vzeti iz A: osrednjega dela plazju, B: iz vrtnice zgornjega dela plazju, C: površina, ista lokacija kot B, D: spodnji del plazju

In order to determine the parameters required for numerical simulations of the earth flow with the FLAC program, the rheological tests of the samples having water content of 40 % and 50 % were performed under non-destructive shear conditions. Measurements showed that the investigated samples with water content of 40 % exhibited viscoelastic behaviour with predominant elastic contribution to the viscoelastic response. From the experimental data measured in creep and recovery tests, the parameters of the Burger model were evaluated.

The Burger model (Barnes, 2000) describes the response of many real viscoelastic materials on the applied constant shear stress (τ_c) in the range of linear response. It consists of four simple mechanical elements, two springs (G – elastic modulus) and two dash-pots (η – viscosity) and represents a combination of the Maxwell (describes viscoelastic-liquid response) and the Kelvin-Voight (describes viscoelastic-solid response) mechanical model in a series (Figure 6).

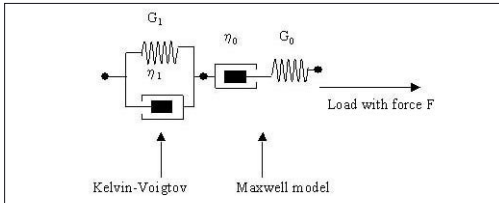


Figure 6. Burghers mechanical model – a combination of Kelvin-Voight mechanical model and Maxwell model

Slika 6. Burghersov model sestavlja zaporedno vezana Kelvin-Voightov in Maxwellov model

The Burger model describes shear deformation (γ) of the material during creep tests as:

$$\gamma(t) = \frac{\tau_c t}{\eta_M} + \frac{\tau_c}{G_M} + \frac{\tau_c}{G_K} \cdot \{1 - \exp(-t/\lambda_K)\}$$

$$\text{and } \gamma(t) = \tau(t)/G(t) = \tau_c/G(t)$$

where λ_K represents the Kelvin-Voight relaxation time, $\lambda_K = \eta_K/G_K$ and τ_c the applied shear stress and $G(t)$ the time dependence of the shear modulus. The Burger model is often written in terms of time dependence of compliance $J(t)$, which is defined as [$J(t) = 1/G(t)$]. This means that time dependence of shear deformation can be written as:

$$\gamma(t) = \tau(t) \cdot J(t) = \tau_c \cdot J(t)$$

Then the Burger model can be expressed:

$$J(t) = \frac{t}{\eta_M} + J_M + J_K \cdot \{1 - \exp(-t/\lambda_K)\}$$

For the evaluation of the model parameters it is necessary to determine the dependence of $\gamma(t)$ experimentally. Viscous (η_M and η_K) and elastic (G_M and G_K) contributions to the viscoelastic response of the investigated sample, taken from the upper part of the landslide, at water contents of 40 % and 50 %, were calculated from the creep tests. For calculation the examined range of water content was selected in order to compare the model parameters evaluated for the sample with solid-like viscoelastic response ($w = 40\%$) with the sample with fluid-like response ($w = 50\%$). As reported in Table 3, the decrease of humidity in the examined range increased the values of material properties by at least ten times. The experimental data and the corresponding curves calculated by using the Burger model are shown in Figure 7. It is evident that the model correlated with the experimental data in a satisfactory way. For calculation of all Burger's parameters the SOLVER protocol in Excel was used. Experimental data from creep and recovery curve were fitted with Burger's parameters.

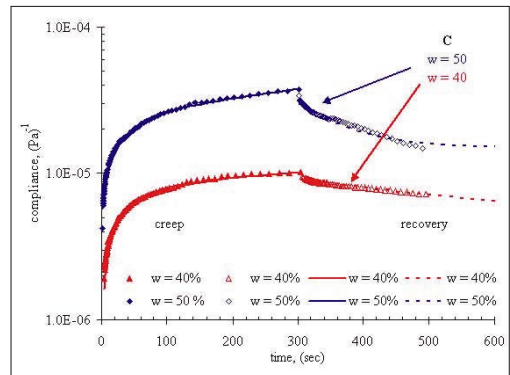


Figure 7. Creep and recovery tests for the sample taken from the upper part of the landslide at water content of 40% and 50%. Curves passing the experimental data are correlated by the Burger model

Slika 7. Test lezenja za vzorce vzete iz zgornjega dela plazju, z vsebnostjo vode 40 in 50 %. Krivulja je korelirana z Burgerjevim modelom

Geomechanical and rheological investigations of landslide materials showed that the material properties of the samples are strongly influenced by water content, as

well as by the time in which the materials were exposed to wetting, therefore by the precipitation conditions on the landslide.

During drilling, influx of underground water was observed in layers at different depths.

Numerical analyses

The aim of numerical modelling was to establish the most critical parts of the landslide and the mechanism of failure. For the calculation, the FLAC program was used. This is an explicit finite difference program that performs Lagrangian analyses.

Because of the large dimension of the landslide, it was divided for the numerical calculations into 5 regions. Each region begins and finishes with stable layers of sandstone. In that way the influence of the border effects was reduced.

Burger - visco-plastic model

The Burger visco-plastic model considers visco-elasto-plastic deviatoric behaviour and elasto-plastic volumetric behaviour. The visco-elastic and plastic strain-rate component act in a series. The visco-elastic part corresponds to the Burger model and the plastic part to the Mohr-Coulomb model.

The deviatoric component was described with the relation:

$$\dot{e}_{ij} = \dot{e}_{ij}^K + \dot{e}_{ij}^M + \dot{e}_{ij}^p$$

where e_{ij}^K – Kelvin strain component, e_{ij}^M – Maxwell strain component, e_{ij}^p – plastic strain component, σ_{ij} – deviatoric stress.

$$\sigma_{ij} = 2\eta^K \cdot \dot{e}_{ij}^K + 2G^K \cdot \dot{e}_{ij}^K$$

$$\dot{e}_{ij}^M = \frac{\dot{\sigma}_{ij}}{2G^M} + \frac{\dot{\sigma}_{ij}}{2\eta^M}$$

$$\dot{e}_{ij}^p = \lambda \cdot \frac{\partial g}{\partial \sigma_{ij}} - \frac{1}{2} \dot{e}_{vol}^p \delta_{ij}$$

where they are; g – potential function, λ , plastic flow parameter, e_{vol}^p – plastic volume strain rate.

The volumetric behaviour is determined with:

$$\dot{\sigma}_0 = K(\dot{e}_{vol} + \dot{e}_{vol}^p)$$

where e_{vol} is volume strain rate.

Results of the Burger visco-plastic model

The Burger visco-plastic model was used only for the gravel landslide mass. The aim of this calculation was to simulate the earth flow of the landslide gravel mass at the time of the largest movements. For the flysch layers, the Mohr-Coulomb model was used. Input geomechanical and rheological data are given in Table 4.

Table 4. Geomechanical parameters for the Burger visco-plastic model of gravel and slide mass

Tabela 4. Geomehanski parametri za Burgerjev visko-plastičen model za splazelo maso

γ KN/ /m ³	E MPa	ϕ °	c KN/ /m ²	ν	G_M MPa	η_M Pas	G_K MPa	η_K Pas
21	3	24	1	0,3	1,11e6	1,3e9	1,53e5	5,02e6

Considering the material properties in the Burger visco-elasto-plastic model, the maximal deformations developed in one day were calculated with numerical simulations.

At the time of maximal landslide movement the observed deformations were in the range of 60–100 m/day. The best results of numerical simulations were obtained when the geomechanical parameters were taken into account for the material water content ranging between 35 and 40 %. With these material properties, taken at different parts of the landslide, the simulated deformations were in the range 70–80 m/day.

The results of the numerical analyses are presented in Figure 8, from the upper part of the landslide to the bottom. At the end of the landslide, several meters thick layer of sandstone represents a natural barrier before the village. There was an important question whether that thick layer of sandstone was strong enough or whether it could collapse under additional gravel landslide mass from the upper part of the landslide. Geomechanical investigation proved, with inclinometer measurements, that the natural barrier is stable. Also numerical analyses confirm that it is stable even under additional landslide mass. In the case of landslide moving, the landslide mass will pour over the sandstone layer, but the natural barrier of sandstone will remain stable.

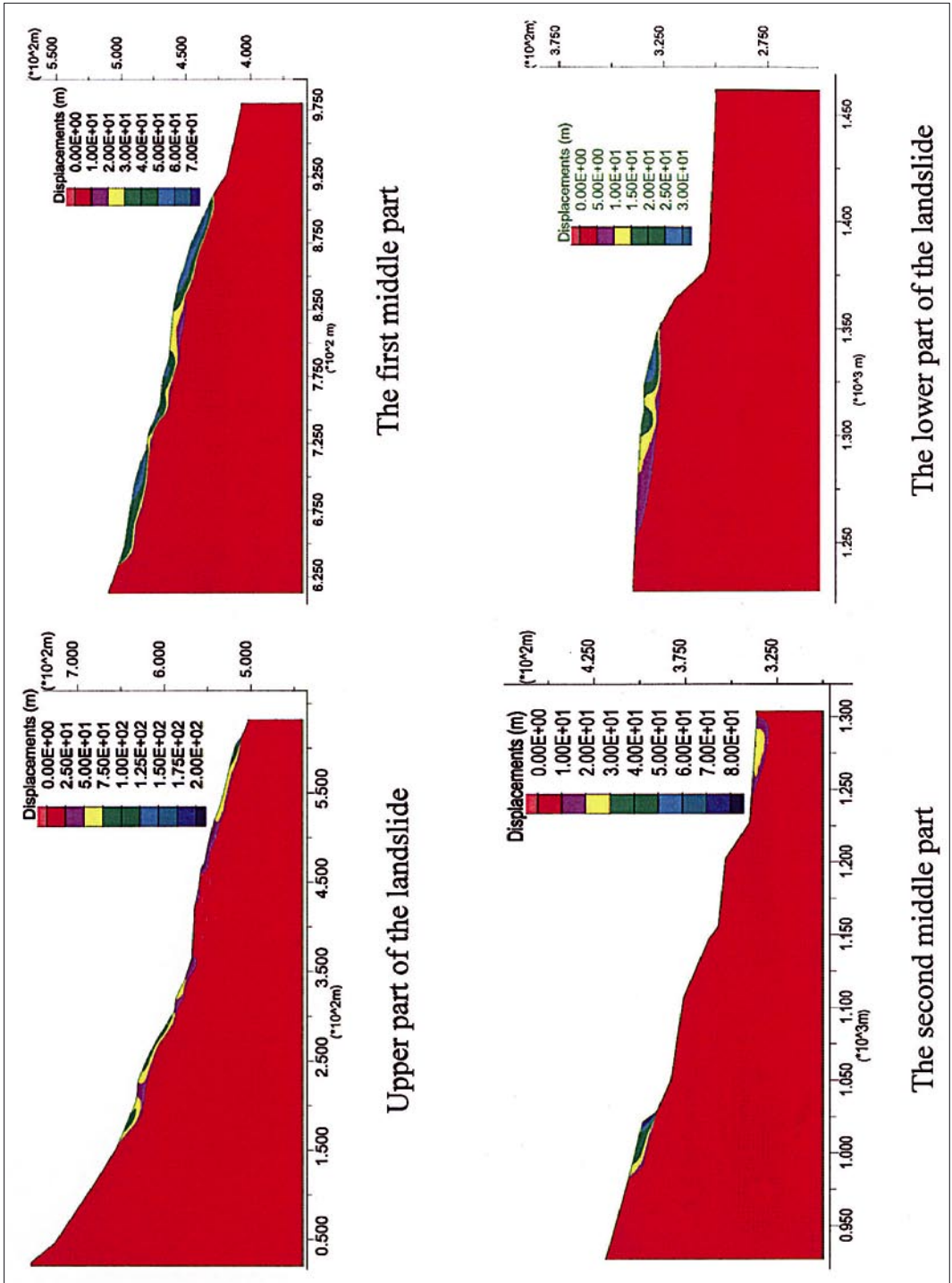


Figure 8. Results of Burger elasto-plastic mode; displacements per day
 Slika 8. Rezultat izračuna z Burgerjevim visko-plastičnim modelom; premiki na dan

Conclusions

With the visco-plastic Burger model the rheological characteristics of gravel landslide mass were considered. Taking into account also the rheological properties of the materials at different landslide locations, the model allowed us to describe the actual situation on the landslide. In this way, we were able to simulate even the largest deformations when the smallest particles fraction had a water content between 35 and 40 %. The Burger model is not often used for this type of geotechnical problem. Our experience is that together with good rheological tests it could present quite a reliable prediction of landslide movement with time.

Geomechanical laboratory tests showed that shear properties depend on the percentage of moisture. The samples taken from boreholes during a wet period had poorer geomechanical properties than those taken during a dry period, but the evaluated results did not differ drastically. Greater differences were observed from rheological characterisations. For example, the viscosity changes were in the range between 10^3 and 10^8 Pas, depending on the content of water.

Five reinforced concrete wells – dowels were constructed in the upper part of the landslide in year 2005. Wells were used for dewatering and as a retaining structure. Until that larger movements on landslide have not observed.

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