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Finite element modelling of a creeping slope using viscohypoplasticity

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ABSTRACT: Modelling of slow-moving landslides and creeping slopes and predicting their rate of movement can provide important information to reduce risk and related costs. However, numerical modelling of landslide movements that accounts for soil mechanical behaviour is scarce in literature, especially when rate-dependent mechanical behaviour such as creep is considered. In this contribution, we investigate usability of viscohypoplasticity for predicting rate of movement of slow-moving landslides. It is done first in a parametric analysis using simple slope geometry of the influence of viscous soil parameters and model geometry on the predicted displacement evolution with time. Furthermore, we present a 2D viscohypoplastic analysis of a cross-section of a creeping slope with highway embankment in the northern part of the Czech Republic. The modelled area is affected by deep rock block spreading with slow creep deformations of basalt blocks sliding on plastic basal marlstones – the viscohypoplastic model is used to model creep deformations in the shearzone. The model parameters are calibrated by a back-analysis of the inclinometer data. It is shown that inclinometer measurements and their evolution in time compare well with model predictions.

Keywords: *landslide; creep; hypoplasticity; time-dependency; rate effects*

1 INTRODUCTION

Creeping slopes and slow-moving landslides are a common type of slope deformation. Even though usually not catastrophic, they can cause serious damages to infrastructures and even may be a precursor of a rapid slope failures (Mansour et al., 2011; Lacroix et al., 2020). Modelling of slow-moving landslides can provide important information to reduce risk and related costs, but numerical modelling that accounts for soil mechanical behaviour is scarce in literature, especially when rate-dependent mechanical behaviour such as creep is considered. Substantial amount of work has been done on Portalet landslide in the Pyrenees – Fernandez-Merodo et al. (2014) presented viscoplastic 2D hydro-geomechanical finite element model with rate-dependent displacement – porewater pressure formulation, the constitutive viscoplastic model is based on Perzyna's theory with a Mohr–Coulomb rupture criteria. Bru et al. (2018) presented a continuation of the work by applying the method for 3D analysis of landslide kinematics. De Novelis et al. (2016) used different approach to model viscous effects in Ivancich landslide (Assisi, Italy) – they described the soil material behaviour as Newtonian fluid characterized by viscosity constant over time (steady state viscous flow).

In this work, we employ viscohypoplastic model by Jerman and Mašín (2020) to predict rate of slope movements. First, a parametric analysis is employed to examine model performance, influence of geometry and viscohypoplastic model parameters. Subsequently, the model is used in a 2D rate-dependent analysis of a creeping slope with highway embankment in Prackovice landslide area.

2 CONSTITUTIVE MODEL

Rate-dependent behaviour of the layer above the zone where creep deformations occur (further called "shearzone" to keep the landslide nomenclature) was described by viscohypoplastic model by Jerman and Mašín (2020). The advanced viscohypoplastic model is based on critical state soil mechanics framework, takes into account nonlinearity on soil behaviour and time-dependent mechanical behaviour**.** Generally, the models based on hypoplasticity framework are defined by a single equation expressing the stress rate as a non-linear function of stress, stretching tensor and void ratio (Mašín, 2019). The stiffness tensor is non-linearly dependent on the strain rate direction. Viscohypoplastic model formulation is based on the time-independent hypoplastic model for clays (Mašín, 2005; Mašín, 2014).

Basic rate formulation of the viscohypoplastic model reads:

$$\mathring{\mathbf{T}} = f_s(\boldsymbol{\mathcal{L}}:\mathbf{D} + f_d\mathbf{N}D_r) \tag{1}$$

where $\mathring{\mathbf{T}}$ is the stress-rate tensor, $\mathbf{D}$ is the Euler stretching tensor, $\boldsymbol{\mathcal{L}}$ and $\mathbf{N}$ are the fourth and second order constitutive tensors, respectively. f_s is the barotropy factor (function of mean stress p) and f_d is the pyknotropy factor:

$$f_d = \left(\frac{2p}{p_e^*}\right)^{1/I_v} \tag{2}$$

where p_e^* is Hvorslev equivalent pressure calculated from the normal compression line formulation

$$\ln(1+e) = N - \lambda^* \ln\left(\frac{p}{p_r}\right) \tag{3}$$

where parameters N and λ^* define the position and slope of the isotropic normal compression line with p_r being the reference stress 1 kPa. For detailed mathematical formulation of clay hypoplasticity the readers are referred to relevant publications (Mašín, 2014) and for detailed viscohypoplastic model description, mathematical formulation, and validation on the scale of elements tests, see Jerman and Mašín (2020) and for examples of its validation Jerman and Mašín (2021) and Jerman et al. (2022). The model implementation within an element test driver is freely available at soilmodels.com/triax.

The parameters used in the model can be separated into two groups: 1) Parameters used in the basic hypoplastic model for clays by Mašín (2014) - φ_c, λ^*, N, κ^* and ν, which are standard critical state soil mechanics parameters equivalent to Modified Cam-clay model parameters; 2) Parameters defining rate effects (Niemunis et al., 2009; Jerman and Mašín, 2020) - D_r, I_v. For details on parameter definition and calibration see Jerman and Mašín (2020). D_r $[s^{-1}]$ is the reference (creep/loading) rate, which is related with the reference asymptotic state boundary surface specified by overconsolidation ratio (OCR) equal to one. Consequently, D_r defines positions of the rate-dependent normal compression line. The viscosity index I_v controls the influence of OCR on the rate-dependent position of the isotropic and oedometric normal compression lines, the rate-dependent undrained shear strength c_u, as well as the creep and relaxation rates.

3 PARAMETRIC ANALYSIS

The reliability of the application of viscohypoplasticity for modelling the rate of movement of slow-moving landslides was tested in the PLAXIS 2D software via a parametric analysis described in this section. Three FEM model geometries were created with slope inclination of $\beta = 5.7°, 11.3°$ and $21.8°$, for each slope inclination the thickness of the upper layer above shearzone was kept constant at 25 m, see Figure 1. The time-dependent shearzone was simulated to be 0.5, 1.0 or 2.0 m thick. For each geometry, mesh dependency and parametric analysis of viscohypoplastic model parameters were investigated. To fully test the influence of soil state, various initial void ratios were tested.

3.1 Settings and initial conditions

Simulations were performed in drained conditions only and without the presence of groundwater. The following slope evolution represented by staged construction was adopted to represent slope deformations of natural slopes:

1. Calculating initial stresses and void ratio using Gravity loading
2. Time-dependent analysis using viscohypoplasticity.

The calculations were performed as time-dependent elasto-plastic deformation analysis in Plaxis 2D software with the time interval of 365 days. In the parametric analysis investigating influence of step-size on model predictions maximum time increment per individual step was determined to be 0.005 (i.e. 1.825 days).

Parameters determined in the back analysis of the case study of Prackovice landslide area were used as benchmark values of viscohypoplastic model parameters used in following parametric study. The parameters are summarized in the Table 1.

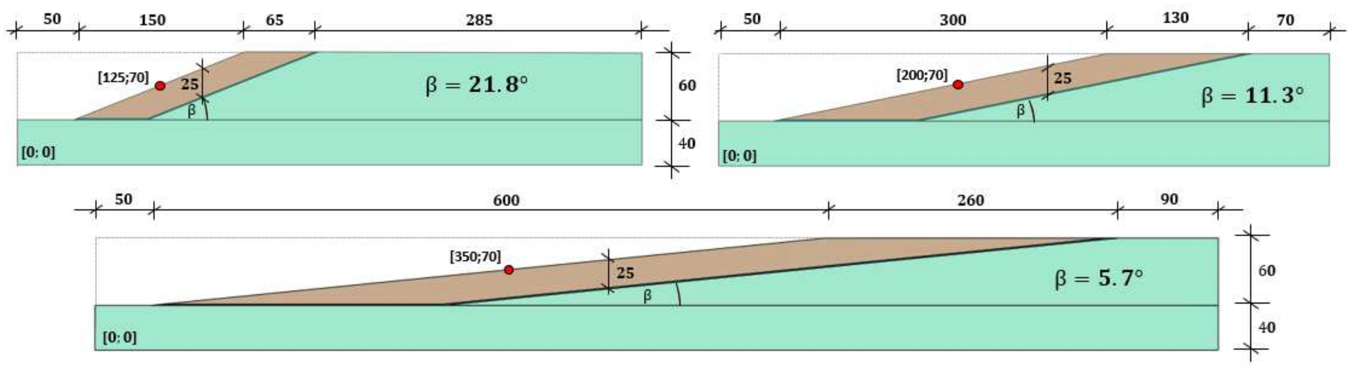

Figure 1: Three FEM model geometries were created with slope inclination of $\beta = 5.7°, 11.3°$ and $21.8°$. Model dimensions in meters. The reference point is marked by a red dot. Upper layer simulated using clay hypoplasticity or Mohr-Coulomb in brown, in green linear elastic layer representing rock-mass with high stiffness. In-between is the shearzone layer simulated using viscohypoplasticity with thickness of 1 m.

Table 1: Viscohypoplastic model parameters used as a benchmark value for the parametric study.

γ_{sat} [kN/m^3]	φ_c [°]	N [-]	λ^* [-]	κ^* [-]	ν [-]	D_r [s^{-1}]	I_v [-]
20	24.5	1.79	0.151	0.007	0.2	0.005	0.09

Also, the parameter p_t, defining mean stress translation and thus artificial tensile strength, was set to a nonzero low value ($p_t = 2$ kPa) to improve numerical stability. It is to ensure no failure occurs in the model due to low stresses at the ground surface in elastic-plastic deformation analysis. Two variants of the upper layer (brown in Figure 1) were used – layer simulated using (1) clay hypoplasticity (Mašín, 2014) or (2) Mohr-Coulomb model – with the parameters summarized in Table 2. Material parameters of the upper layer were determined in the back analysis of the case study of Prackovice landslide area. The soil below the shearzone was simulated using standard linear elastic model (γ_{sat} = 23 kN/m^3; E = 200*10^3 kN/m^2; ν = 0.1).

Table 2: Two variants of the upper layer – layer is simulated using (1) clay hypoplasticity or (2) Mohr-Coulomb model.

Clay hypoplasticity						
γ_{sat} [kN/m^3]	φ_c [°]	N [-]	λ [-]	κ [-]	ν [-]	e_{init} [-]
20	28	1.79	0.151	0.007	0.2	1.0
Mohr-Coulomb						
γ_{sat} [kN/m^3]	φ [°]	c [kN/m^2]	E [kN/m^2]	ν [-]	ψ [°]	
20	28	1	50*10^3	0.2	0	

3.2 Mesh dependency

Models with different number of FEM mesh elements were used to evaluate predicted displacements. If not stated otherwise, we evaluate results by analyzing predicted horizontal displacements (u_x). When upper layer was simulated using Mohr-Coulomb model, mesh dependency was observed across the whole mesh spectrum investigated. The mesh setting influences localization of the deformation in the upper layer, but also distribution of predicted displacements, see Figure 2. On the other hand, the simulations with relatively high φ_c (resulting in factor of safety of the slope around 2) and low OCR hypoplastic upper layer show no localization and thus no mesh dependency. With higher slope inclination (see Figure 7) and higher OCR localization appears also in hypoplastic upper layer, which leads to mesh dependency for models with low number of elements (<3000), however, the simulations are generally more robust using hypoplastic upper layer. It was determined that mesh density in the shearzone (simulated by viscohypoplasticity) has no influence on the model predictions.

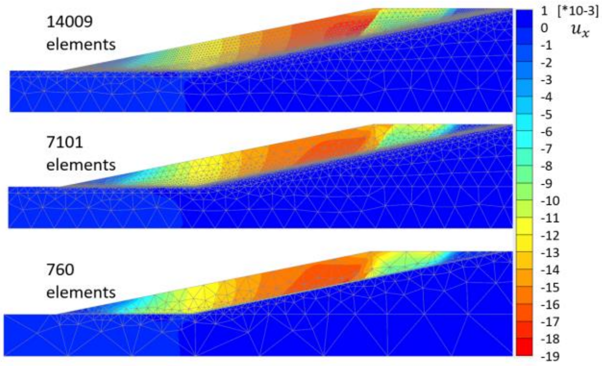

Figure 2: Observed mesh dependency of the predicted displacements (u_x) for three mesh settings with the upper layer simulated using Mohr-Coulomb model.

3.3 Constitutive model parameters

The shearzone layer was simulated using viscohypoplastic model. The parametric analyses were done both for the hypoplastic and Mohr-Coulomb upper layers. However, as the hypoplastic upper layer has been shown to be mesh independent and thus allowed us to use less computationally demanding simulations, we present the hypoplastic upper layer in most examples. First, we present influence of the critical state friction angle on the predicted slope horizontal displacements (u_x), which are shown in Figure 3 and Figure 5 for three values of φ_c – 14° (equivalent to the residual strength of the marlstones presented in the case study), 24.5° and 29°. The lower the φ_c the higher the predicted u_x, lowering of φ_c also increases extent of the zone, where measurable deformations in the slope occur. Further, influence of viscosity index (I_v - parameter governing time-dependent response of the soil) on predicted displacements was evaluated – see u_x at the reference point for various values of I_v after 365 days in Figure 4. Figure 5 shows that increasing I_v increases predicted slope displacements (the displacement distribution is similar to the effect of φ_c in Figure 3). Note different evolution of u_x for low φ_c (rate decreases in time significantly) vs high I_v (only modest decrease of rate) in Figure 5. The value of 0.091 was determined in the back analysis of the Prackovice landslide in Section 4.

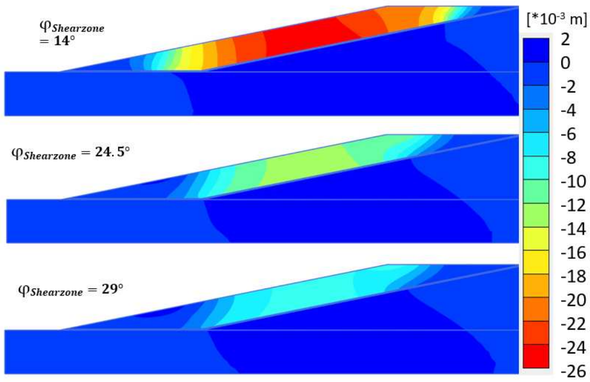

Figure 3: Influence of critical state friction angle of the shearzone on the predicted displacements (u_x). Upper layer simulated by hypoplastic model for clays.

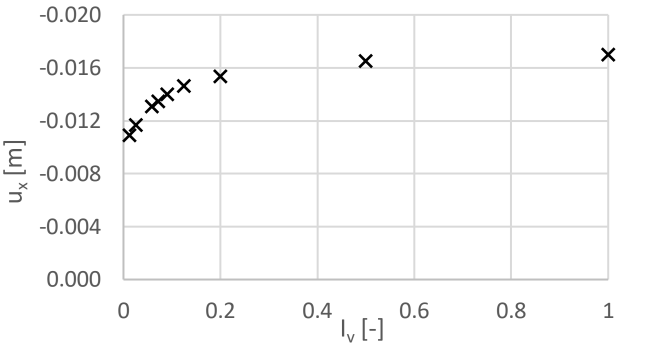

Figure 4: Influence of viscosity index of the shearzone on the predicted displacements (u_x)at the reference point after 365 days. Upper layer simulated by hypoplastic model for clays.

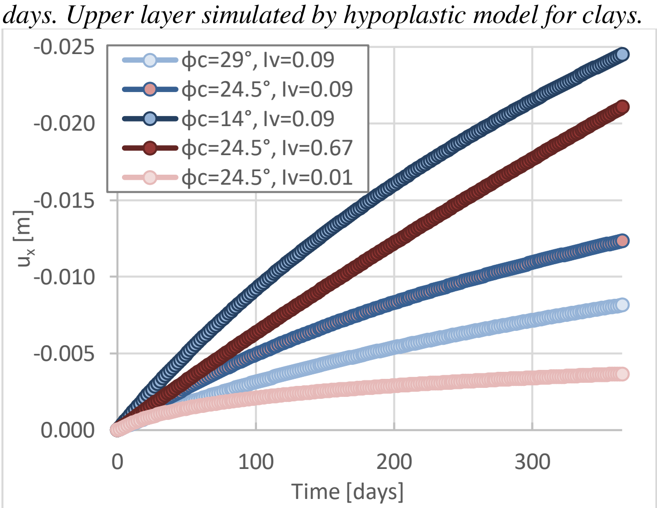

Figure 5: Influence of viscosity index and critical state friction angle of the shearzone on u_x, evolution of u_x in 365 days. Upper layer simulated by hypoplastic model for clays.

Last, Figure 6 presents the influence of the initial OCR of the shearzone layer on the predicted displacements – for lower initial OCR we obtain higher predicted displacements. Mohr-Coulomb upper layer is shown to demonstrate how various shape of localizations of plastic deformations can occur in the upper Mohr-Coulomb layer – see different shapes of shear bands for OCR = 1.1; 1.6, 1.9 and 2.3.

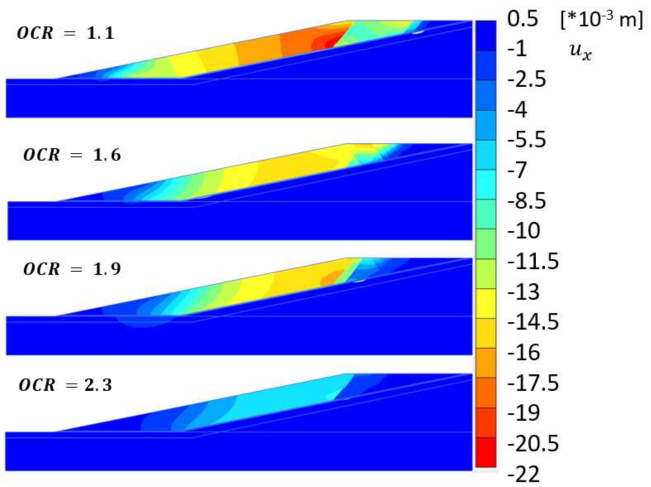

Figure 6: Influence of the initial OCR of the shearzone on the predicted displacements (u_x). Upper layer simulated by Mohr-Coulomb model.

3.4 *Slope geometry*

Influence of slope geometry on model predictions was also investigated. Three FEM model geometries with slope inclinations of $\beta = 5.7°, 11.3°$ and $21.8°$ were created (see Figure 1). The results of the analysis with different slope inclinations are displayed in Figure 7. As expected, slope inclination has significant influence on predicted displacements – for $\beta = 5.7°$ we obtain approximately 5 times lower maximal predicted displacements compared to $\beta = 21.8°$. For steeper slope we also see more prevalent localization in hypoplastic upper layer, qualitatively similar to the solution with Mohr-Coulomb upper layer. Further, effect of the shearzone thickness (h) was studied. Simulations were run for h = 0.5; 1.0 and 2.0, and they confirmed that the predicted displacements were proportional to h, which has been expected (for the given shear strain magnitude, shear displacement depends on shear band thickness).

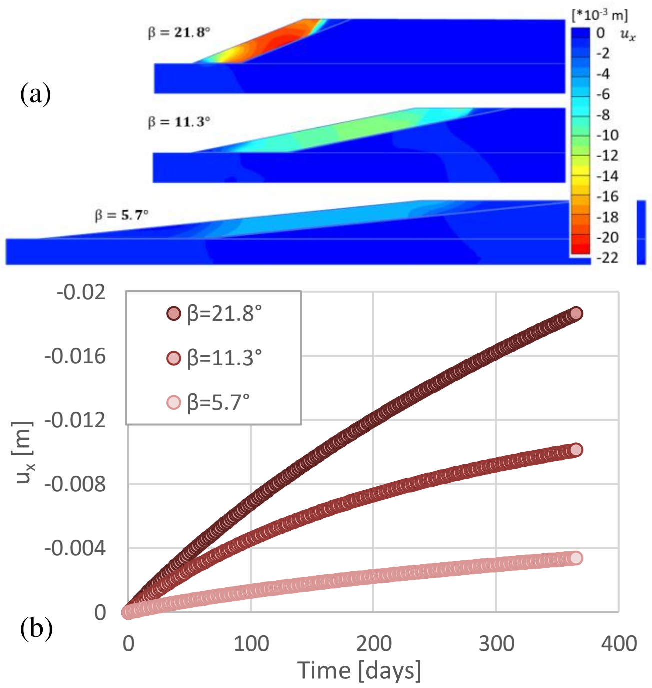

Figure 7: Three FEM model geometries with slope inclination of β = 5.7°, 11.3° and 21.8°. Hypoplastic upper layer. (a) Predicted displacements. (b) Graph showing evolution of predicted displacements in time in the reference point.

4 CASE STUDY: PRACKOVICE LANDSLIDE AREA

The use of viscohypoplastic model for predicting slope movements is validated using the case of Prackovice landslide area. The Prackovice landslide area lies in Ústí nad Labem Region, Czech Republic in the western part of Central Bohemian Uplands, represented by a rolling terrain of eroded Cenozoic sediments, which is locally penetrated by individual volcanic domes and cones (Pánek et al., 2016). The landslide area lies at the connection of the regional geological units of the Central

Bohemian Uplands Neogene volcanic rocks and Cretaceous sedimentary rocks (silty marls to marlstones from the Březno Formation) of Bohemian Cretaceous basin (Ulrych et al., 1999). The rich in smectite marlstones are characteristic with low critical and residual strength and its high susceptibility to landsliding as discussed by Rybář et al. (2000) and Roháč et al. (2020). The area is affected by fossil deep-seated slope deformations (which can reach thickness of up to 40 meters). The slope movements can be characterized as very slow to extremely slow rock block spreading and soil creep by the Varnes classification (Hungr et al., 2014) or as deep-seated block sliding on a basal plastic zone (Němčok et al., 1972). The blocks are formed by basaltic rocks from lava flows, while the basal plastic zone is formed by plastic marlstones. The D8 highway embankment (at the highest point 18 meters high) constructed in 2009 is in the middle of the cross-section (see Figure 8a).

4.1 Model description

Deformation analysis was conducted via FEM modelling in Plaxis 2D software. The groundwater levels used in the simulations are based on the 3D hydraulic model created by Říčka and Kuchlovský (2020). Two groundwater levels were used to simulate seasonal groundwater level oscillations. At the beginning of the simulation, stresses are generated, and void ratio is calculated (similarly to the parametric analysis), in this case OCR was initialized to 1.9. The subsequent steps are constructed in such a way that the structure of the model is equivalent to the sequence of the highway construction. Thus, first, a construction of the embankment is simulated (2009), which is followed by plastic rate-dependent calculation – where creep as well as time-independent deformations due embankment construction occur (2009 – 2022). The viscous parameters (D_r, I_v) of the viscohypoplastic model were calibrated via a manual back-analysis of inclinometer data from time interval 2016-2022 (as inclinometers were installed between 2016 and 2020), for which four inclinometers were used. Other (standard clay hypoplasticity) parameters were calibrated with laboratory data of triaxial and oedometer tests. Note the viscohypoplastic model was used in all stages of the model and thus the creep also influences embankment construction. The geometry of the cross-section is based on 3D engineering geological model of the area by Kycl et al. (2020), see Figure 8a.

4.2 Results

The results of the viscohypoplastic rate-dependent simulations of a cross-section through D8 highway embankment are shown in Figure 8b for predicted horizontal displacements u_x and in Figure 8c for predicted total

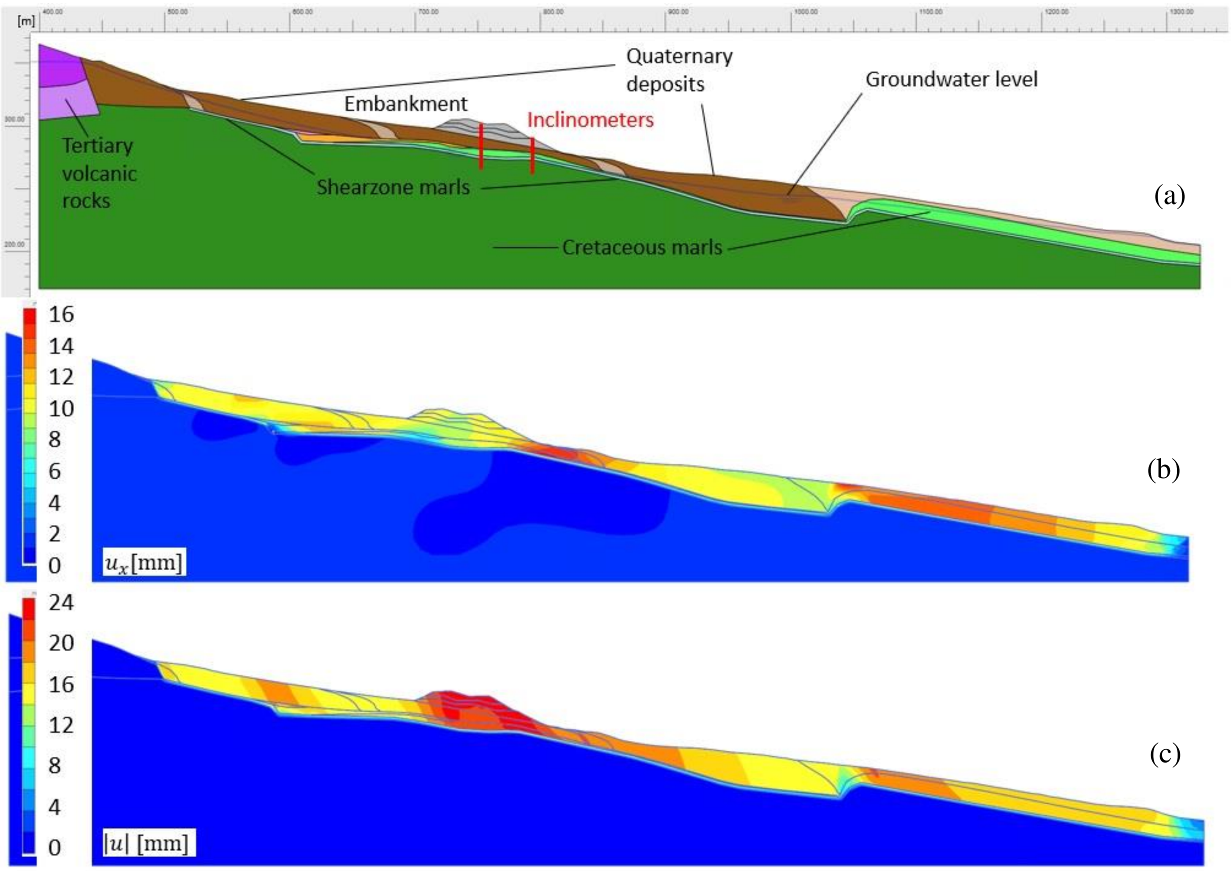

Figure 8: (a) Geology and geometry of the cross-section used to predict slope movements using viscohypoplastic model, its three main geological units – Cretaceous marls and marlstones, Tertiary volcanic rocks and Quaternary deposits composed of basaltic rocks from lava flows and clayey colluvial deposits between them. Predicted horizontal (b) displacements and total (c) displacements for years 2019-2022.

displacements $|u|$. The results are presented for time interval 2019-2022 to show displacements which are less influenced by deformations induced by embankment construction in 2009. In agreement with the parametric analysis, higher predicted displacements are observed in the areas with steeper slope. Figure 9 shows inclinometer measurements compared with model predictions for years 2019-2022, note the seasonal oscillations predicted by the model.

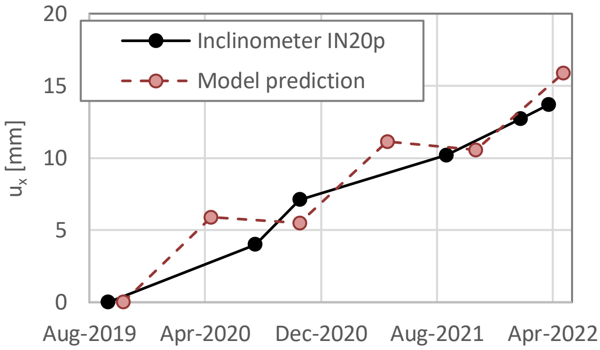

Figure 9: Inclinometer data compared to model predictions.

5 SUMMARY AND CONCLUSIONS

In this contribution we analysed usage of viscohypoplastic model for predicting slow creep movements of slow-moving landslides. The viscohypoplastic model was used to simulate behaviour of the shearzone, while the upper layer was simulated by both clay hypoplasticity and Mohr-Coulomb model. We first investigated model performance in a parametric analysis using a simple slope geometry. The influence of slope inclination and thickness of the shearzone were assessed. Mesh dependency and the effects of model parameters and initial conditions (OCR) were investigated. We have shown that predicted slope displacement evolution with time can be controlled by setting soil viscous parameters. Viscohypoplastic model was further used to simulate a 2D case study of a creeping slope in Prackovice landslide area, where constitutive model parameters were obtained via back analysis of inclinometer data. It has been shown that inclinometer measurements and their evolution in time compare well with model predictions.

6 ACKNOWLEDGEMENTS

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