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ANALYSIS THE EFFECTS OF THE DEGREE OF SATURATION ON THE SLOPES STABILITY USING MODELLING AND NUMERICAL SIMULATION

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ABSTRACT: Soil materials have been often considered in saturated condition for landslide analyses, in which back pore water pressure has been indicated to be a cause of the landslide. In this paper, numerical simulations are used to analyze the landslide process at the river bank from the viewpoints of unsaturated soil mechanics. A coupled hydro-mechanical model is adopted to numerically simulate the landslide process. For the mechanical behavior, the modified Barcelona Basic Model (BBM) is used in order to take into account the hardening and softening due to mechanical and hydraulic loading and unloading as well as to describe the shear strength via critical state line. Modified BBM allows the more realistic description of the behavior of soils, and particularly clayey soils in case these soils are not saturated. The numerical simulation using a modified BBM model is compared with the model, which does not account for the states of water saturation such as Drucker-Prager model. Both models are applied to the numerical simulation of the Red River bank in Vietnam. The evolution of displacements and the inelastic deformation during the infiltration process are discussed based on the simulation of dry to the rainy season with the changes of water level. With the model, the authors attempt to point out one of the possible causes leading to the instability of the river bank.

Keywords: Slope instability, Barcelona Basic Model, Elasto-viscoplastic model, Unsaturated soil; Red River

1. INTRODUCTION

Numerous landslides have occurred recently along the bank of the Red River, Hanoi, Vietnam (Fig.1). Reasons have been pointed out: featured geology profiles, the properties of the soil layers, the specific topography-geomorphology, the particularity of the hydrography profile, the characteristics of the flow in seasons, and human activities influencing the geo-environment [1]. The causes of landslides or soil topple at Red River should be studied in both global as well as local viewpoints. In several cases, landslides phenomenon in river bank is interpreted by the back-pore water pressure, when the river water level decreases rapidly inducing the pressure force from the body to the river. However, in many cases the water level of the river reaches far from the top of the river bank, the landslides are still occurring. These phenomena should be studied within the framework of partially saturated soil mechanics.

In order to analyze the stability of the slope, the relationship between stress and strain is calculated by a material model. The material model is described generally by a set of mathematical equations. The General Limit Equilibrium (GLE) method is afterward applied to calculate factors of safety via commonly used methods of slices (Bishop's simplified method, Ordinary method of slices) or mass methods (Culmann's method; Fellenius-Taylor method). Commonly used models presently are Mohr-Colomb model, Drucker-Prager model, Hardening model, Soft Soil model, Cam Clay model, etc. However, such classical models do not allow simulating the hardening or softening behavior due to wetting and drying process that occurs in reality.

Fig.1 Red River bank landslide examples [2]

Red River is embanked majorly by clayey levees. Besides several concrete walls were built at the border of the city. In this paper, the stability of these levees depending on the dry and rainy season changes is analyzed. Water level lowers in the dry season and the levee's body, which is made of soil, becomes dry. Water level increases in the rainy season and this may be a possible trigger bringing the slope to an unstable state because an increase of water level to the levee footing causes softening in the soil stiffness and decreasing the soil shear strength at the footing. The water is sucked up due to capillary pressure, thus generating higher water content or higher bulk density of the soil and therefore the levee body suffers more body pressure. This phenomenon induces an increase of the settlement at the levee footing and it could be a reason for the instability of the levee body. These processes will be studied by numerical simulations in the paper.

In this study, a coupled hydro-mechanical code [3] for unsaturated soil is used for the numerical simulation of the landslide process. For describing the mechanical behavior, an elasto-viscoplastic model based on the Barcelona Basic Model (BBM VP) is used [4]. The BBM allows simulating the hardening and softening behavior due to loading and unloading process or wetting and drying process. By including visco-plasticity time and strain rate effects are taken into account [5,6]. In case the soil pore system is occupied by water and air, the multiphase flow is considered, and it is described by the generalized Darcy's law with a conductivity coefficient depending on the degree of saturation [7]. Pore-water suction and the degree of saturation are related via the two-parameter van Genuchten model [8]. In summary, the coupled hydro-mechanical model allows to numerically simulate more realistically the behavior of the soil involved in riverbank problems. The BBM-VP based calculations in this paper are performed using the fully coupled hydro-mechanical finite element code CODE_BRIGHT [9,10]. Furthermore, a viscoplastic Drucker-Prager model (DP-VP) is also using in the numerical simulation. The results of the two models are compared and discussed in this paper.

2. FORMULATION OF THE CONSTITUTIVE MODEL

2.1 Stress-Strain Constitutive Models

In unsaturated soil, suction s is the subtraction of gas pressure P_g and liquid pressure P_l. Suction is zero when the soil is saturated. Net stress $\sigma^{'}$ in unsaturated soil will be effective stress when the soil is saturated (Eq. (1)).

$$\begin{aligned} &s = \max\left[\left(P_g - P_l\right); 0\right] \text{ and} \\ &\sigma' = \sigma^{total} - \max(P_g ; P_{\rm l}) \\ &\Rightarrow p' = p^{total} - \max(P_g ; P_{\rm l}) \end{aligned} \qquad (1)$$

where σ^{total} is the total stress, p^{total} is the total mean pressure, p' is net mean pressure in the unsaturated case or effective mean pressure in the unsaturated case.

The model considered here is an elasto-viscoplastic model for unsaturated soil based on the BBM [4] or on the Drucker-Prager failure criterion [11]. The viscoplastic term is introduced herein in order to slightly control the settlement rate, in which the numerical convergence is guaranteed at each time step. The general concept of viscoplasticity based on the Perzyna theory is used [12]. Following the visco-plastic concept, the total strain rate $\dot{\boldsymbol{\varepsilon}}$ is a sum of the elastic and visco-plastic strain rates:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\boldsymbol{e}} + \dot{\boldsymbol{\varepsilon}}^{\boldsymbol{vp}} \qquad (2)$$

The elastic part is related to the net stress $\dot{\boldsymbol{\sigma}}'$ through generalized Hooke's law:

$$\boldsymbol{\sigma}' = \boldsymbol{C}^{e} . \dot{\boldsymbol{\varepsilon}}^{\boldsymbol{e}} \qquad (3)$$

where $\boldsymbol{C^e}$ is the elastic stiffness tensor. Following Perzyna (1966), the visco-plastic strain rate is given via:

$$\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{vp}} = \Gamma\langle\varphi(F)\rangle\frac{\partial G}{\partial \boldsymbol{\sigma}'} \qquad \varphi(F) = \left(\frac{F}{F_o}\right)^N \qquad (4)$$

where Γ is the viscosity parameter, $\langle\varphi(F)\rangle$ is a flow function, F is the yield function and F_o is a normalizing constant with the same unit as that of F. Finally, G is the plastic potential.

a) Barcelona Basic Model - Viscoplastic (BBM-VP)

The yield function in BBM model is the same as in the Modified Cam-Clay model [3]. In BBM, F and G are given according to Eqs. (5) and (6).

$$F(q,p,s) = a\frac{1}{3}q^2 - M^2\gamma(p' + p_s)(p_o - p') \qquad (5)$$

$$G(q,p,s) = a\frac{1}{3}q^2 - \alpha M^2\gamma(p' + p_s)(p_o - p') \qquad (6)$$

where M is the slope of the critical state line (see also Eq.(10)), p_s is the tensile strength that follows a linear relationship with suction Eq.(9), p_o is the pre-consolidation pressure that depends on suction Eq.(7), q is the deviatoric stress, γ and a are model parameters and α is the non-associativity parameter.

The pre-consolidation pressure depends on suction Alonso et al (1990) [3]:

$$p_o = p^c\left(\frac{p_o^*}{p^c}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}} \qquad (7)$$

where p^c is a reference pressure, p_o^* is the pre-consolidation pressure for a saturated state, κ is elastic slope in specific volume vs. means stress diagram, $\lambda(0)$ is the plastic stiffness parameters at saturated state. The stiffness parameter at a given suction *(s)* is defined by Alonso et al (1990) [3]:

$$\lambda(s) = \lambda(0)[(1 - r)\exp(-\beta s) + r] \tag{8}$$

where r is a parameter defining the soil stiffness when suction reaches infinity, β is a parameter controlling the rate of increase of soil stiffness with suction.

The dependence of the tensile strength p_s on suction is given by:

$$p_s = ks \tag{9}$$

where k is a parameter that takes into account the increase of tensile strength due to suction.

The parameter M determines the slope of the critical state line and its value depends on suction according to:

$$M(s) = M_{dry} - (M_{dry} - M_{sat})\left(\frac{M_{sat}}{M_{dry}}\right)^s \quad (M_{sat} < M_{dry}) \tag{10}$$

where M_{dry} and M_{sat} are the slopes of the critical state line at the dry and saturated state.

b) Drucker-Prager model Viscoplastic (DP-VP)

In DP-VP model, F, and G in Eq. (4) are given by Eq.(11):

$$G = F = q - Mp' - c'^{\beta_c} \tag{11}$$

In this case, M and β_c are calculated by Eq. (12) to provide the best fit to the Mohr-Coulomb hexagon and ϕ' and c' are the effective angle of friction and the cohesion defining the Mohr-Coulomb failure envelope at the saturated condition.

$$M = \frac{6\sin\phi'}{3 - \sin\phi'} \qquad \beta_c = \frac{6\cos\phi'}{3 - \sin\phi'} \tag{12}$$

2.2 Hydraulic Equations

For the hydraulic process, the advective flow of the water phase is given by the generalized Darcy's law:

$$\mathbf{q}_l = -\frac{\mathbf{k}k_{rl}}{\mu_l}(\nabla P_l - \rho_l \mathbf{g}) \tag{13}$$

where μ_l is a dynamic viscosity of the pore liquid, P_l is the liquid pressure and $\mathbf{g}$ is the gravity acceleration, ρ_l is the liquid density. The tensor of the intrinsic permeability k is defined via Kozeny's model:

$$\mathbf{k} = \mathbf{k_o}\frac{\phi^3}{(1-\phi)^2}\frac{(1-\phi_o)^2}{\phi_o{}^3} \tag{14}$$

where ϕ is the porosity, ϕ_0 is a reference porosity, $\mathbf{k_o}$ is the intrinsic permeability for the matrix with a porosity ϕ_0. The relative permeability, k_{rl}, is expressed according to van Genuchten (1980) [8]:

$$k_{rl} = \sqrt{S_e}\left(1 - \left(1 - S_e^{1/\lambda}\right)^\lambda\right)^2 \tag{15}$$

where λ is a shape parameter for the retention curve. Soil water characteristic curve is modeled via an effective degree of saturation. The effective degree of saturation S_e is calculated as follows:

$$S_e = \frac{S_l - S_{rl}}{S_{ls} - S_{rl}} = \left(1 + \left(\frac{P_g - P_l}{P_0}\right)^{\frac{1}{1-\lambda}}\right) \tag{16}$$

where S_{ls} and S_{rl} are the maximum and the residual degree of saturation, P_0 is a model parameter.

3. MODEL PERFORMANCE IN A BOUNDARY VALUE PROBLEM

3.1 Description of the Boundary Value Problem

The model is applied to simulate the landslide process in the Red River region (Fig.2). The reason for the instability phenomenon is assumed by the water level variation within the two seasons in Vietnam. In the dry season the water level is low and the river bank is unsaturated [13]. Because the soil has high strength at unsaturated state, the top levee can support an existing construction on it. When the rainy season comes, the water level increases to the toe of the levee. With the infiltration process at the toe of the levee, the soil strength decreases and that may trigger off the instability phenomenon.

For numerical simulation of the landslide process, the geometry of the riverbank is simplified as it is given in Fig.3. The simulation process is divided into two stages. Stage 1 corresponds to the conditions during the dry season, when the water level is low, and the top edge of the riverbank is imposed on a distributed load P = 120 kPa. The water lever is taken to be 3.0 meters up from the bottom of the numerical model. Stage 2 corresponds to the conditions during the rainy season, when water level increases. It is assumed in this stage that the water level is 10 cm above the slope toe. The deformation

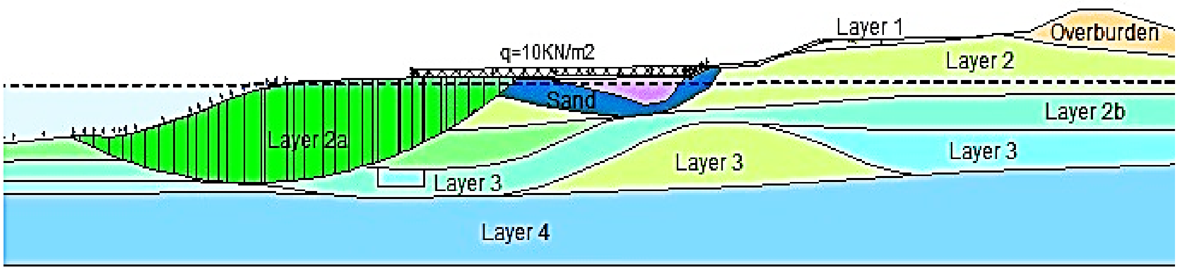


Fig.2 Cross section of the Red River bank [2]

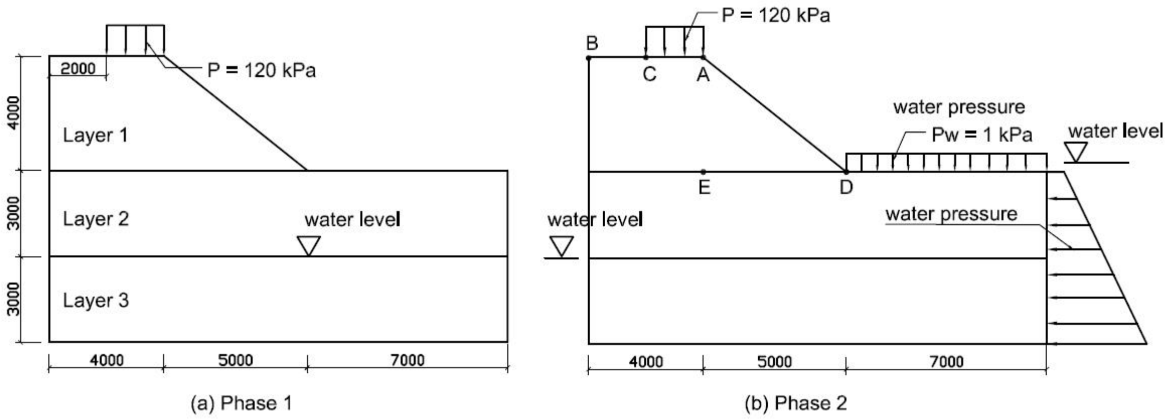


Fig.3 Scheme of the problem geometry for simulating a landslide process

and the suction redistribution are simulated using a fully coupled HM model, namely BBM-VP. For comparison, the authors employ the DP-VP model where the unsaturated flow is considered via the generalized Darcy's law but the coupling between suction and mechanical model parameters is not applied.

In CODE_BRIGHT initial water content is introduced by liquid pressure. Negative liquid pressure is used for the unsaturated state. Positive liquid pressure is used for saturated soil. Gas pressure is assumed to be zero. In order to give water level is 3 meters from the bottom of the model, the water boundary pressure at the bottom of the model Pl = 0.03(MPa). Initial conditions and hydraulic parameters are presented in Table 1.

Table 1a Initial conditions

Parameter	Unit	Layer 1	Layer 2	Layer 3
ϕ_0	-	0.45	0.42	0.40
P_{l0}	MPa	-0.6	-0.05	0
e_0	-	0.818	0.724	0.667

3.2 Model Parameters

The properties of soil at the Red River bank are reported in Tran (2016) [2]. The parameters of Mohr-Colomb model are converted to Barcelona Basic model considering capillary pressure. The other parameters, which cannot be derived from [2], are given in Geise [14]. The materials in Geiser have content and structure are close to that of the levee material. The mechanical parameters for BBM-VP are given in Table 2.

The corresponding parameters for DP-VP are presented in Table 3. The viscosity parameter is taken the same for both viscoplastic laws, i.e. Γ is equal to 250 s^{-1} for layers 1 and 2, and it is equal to 10 s^{-1} for layer 3, see Fig.2.

The water retention curve is expressed via the well-known two-parameter Van Genuchten model [8]. The parameters for the hydraulic constitutive equations are as follows:

Table 1b Hydraulic parameters

Parameter	P_o	λ	k_o	φ_0
Unit	MPa	-	(m^2)	-
Layer 1	0.04	0.3	2.5×10^{-14}	0.3
Layer 2	0.04	0.3	2.5×10^{-14}	0.3
Layer 3	0.04	0.3	1.5×10^{-14}	0.3

Table 2 Parameters for the BBM-VP model

Parameter	Γ	N	F_o	α	γ	M_{dry}	M_{sat}	p_o^*	a
Unit	1/s	-	MPa	-	-	-	-	MPa	-
Layer 1	250	4	1.0	0.3	1.0	1.33	0.6	0.21	3
Layer 2	250	4	1.0	0.3	1.0	1.33	0.6	0.21	3
Layer 3	10	4	1.0	0.3	1.0	1.4	1.1	0.40	3

Table 3a Parameters for BBM-VP model-continuation

Parameter	κ	$\lambda(0)$	R	β	p^c	k	e_o	E	ν
Unit	-	-	-	-	MPa	-	-		-
Layer 1	0.007	0.032	0.2	0.01	0.05	0.01	0.818	50	0.3
Layer 2	0.007	0.032	0.2	0.01	0.05	0.01	0.724	50	0.3
Layer 3	0.007	0.032	0.2	0.01	0.1	0.01	0.667	120	0.3

Table 3b Parameters for DP-VP model

Parameter	φ'	c'	γ_{dry}	γ_{wet}	$\gamma_{initial}$	E	v
Unit	°	-	g/cm3	g/cm3	g/cm3	kN/m2	-
Layer 1	33	8.4	14.6	18.9	15.9	5000	0.3
Layer 2	33	8.4	14.6	18.9	15.9	5000	0.3
Layer 3	33	0.7	15.4	19.4	18.5	12000	0.3

4. RESULTS AND DISCUSSION

4.1 Result of Numerical Simulation Using Coupled HM Model

The line from point A to point E is selected for observation of the displacements and the degree of saturation (Fig.3). In stage 1, the displacements at point A are relatively small as compared to ones at points B and C. In stage 2, the water level increases up to the toe of the levee and the degree of saturation increases that yields a decrease of suction (Fig.4a and 5a). The distribution of the degree of saturation within the levee body is shown in Fig.5a.

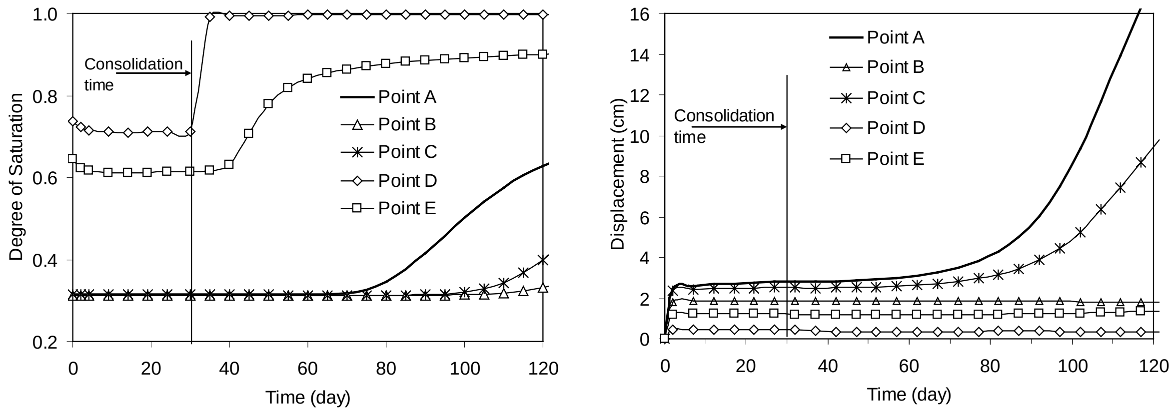
The development of the soil strength and the volumetric softening behavior are modeled according to Eq.(8) and Eq.(10). Consequently, within stage 2 the soil strength at the levee toe is decreasing. As a result, the settlement at point A increases rapidly as compared to the one at point B (Fig.4b). The difference in the displacements at point A and point B may induce a crack and may trigger off the landslide.

In reality, a crack most possibly will develop at the weakest location, e.g. a place with imperfection in levee body or a place with maximum strain deviation. Assuming that the levee body is built of homogeneous materials, the sliding surface can be determined to owe to the localization of plastic deviatoric strain. With this method, the gross sliding surface can be identified as it is shown in Fig.5b.

4.2 Verification Against Drucker-Prager Model

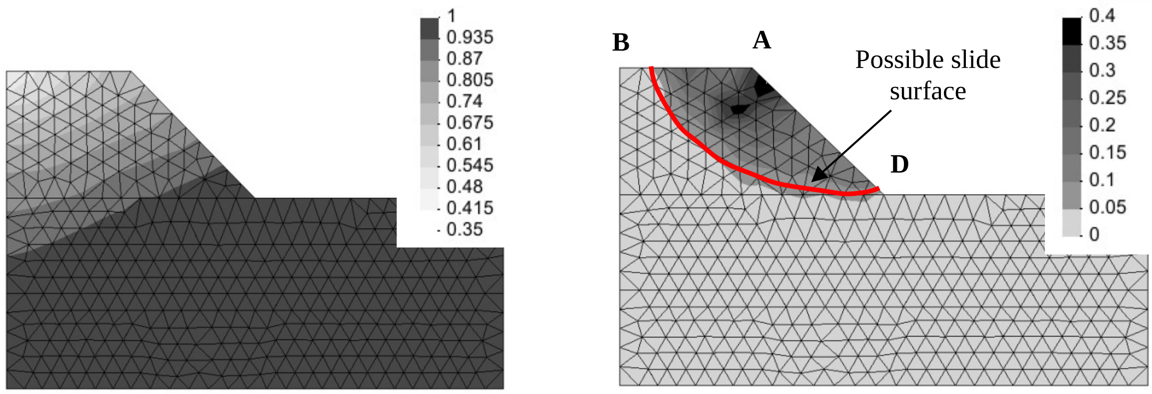
For assessing the efficiency of the fully coupled hydro-mechanical (HM) model, the results obtained using BBM-VP model are compared with the results of the simulation of the process employing other uncoupled models. In the first case, the simulation of the landslide performance was done using the linear elastic-viscoplastic model based on Drucker-Prager failure yield criterion (DP-VP). The DP-VP model as it is implemented in the FE code CODE_BRIGHT takes into account the unsaturated flow, but there is no coupling between suction and the soil stiffness. The hydraulic behavior is considered through a saturated flow via Darcy's law and a prescribed gravitational water level.

Fig.6 presents the evolution of settlement at point A (at the edge of the dike top) and point B (far from the dike edge). In the first stage, the settlement at point A calculated with the coupled HM and BBM-VP model and the settlement obtained via uncouple HM simulation are similar (shown in Fig.6a). In the second stage, because of the reduction of the stiffness and shear strength, the settlement at point A calculated via BBM-VP increases rapidly (shown in Fig.6ab). Table 4 summarizes the difference in the settlement obtained by using the two different models after 150^{th} days. It is shown that the instability of the river bank can occur right at the time when the water level only reaches to the toe of the levee. With the numerical simulation, the paper attempts to interpret the landslide phenomena of the river



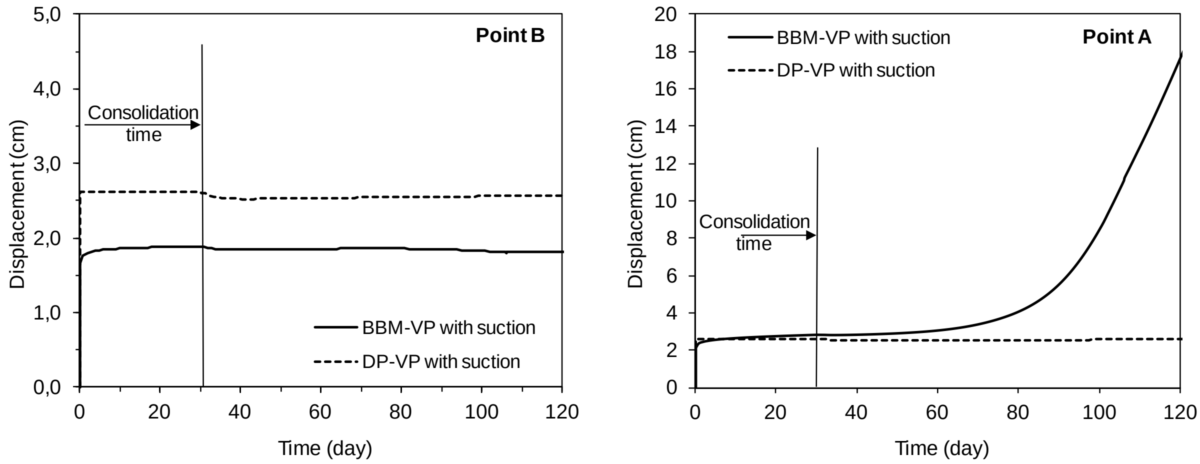
(a) (b)

Fig.4 (a) Displacement vs. time; (b) Degree of saturation vs. time



(a) (b)

Fig.5 (a) Distribution of the degree of saturation on the 150th days; (b) Plastic deviatoric strain on the 150th days



(a) (b)

Fig.6 Displacement vs. time: comparison of different model results. (a) - at point A, (b) - at point B

levees even when it is still unsaturated. However, it is necessary to have a global viewpoint on the instability of the river levees, because this phenomenon may be a combination of different causes e.g. the change of flow, the unusual rainfall, human impacts.

Table 4 Total difference in displacement between points on the 150th days

Model	BBM-VP model	DP-VP model
Point A-B (cm)	40.63	0.13
Point C-B (cm)	17.57	0.49

5. CONCLUSION

Landslide process that may be applicable to the conditions at Red River has been numerically simulated using different mathematical models. An elasto-viscoplastic model for unsaturated soil based on the BBM model was applied for simulating the deformation process due to the water level change and the influence of suction. The obtained results are compared with the results of the simulation of the same process but using different constitutive models. It is observed the dependence of the settlement on the utilized interpretation of the hydro-mechanical process and the influence of the suction and time on the final difference in displacements at the levee top. Whilst, there is no significant change in the displacements between two-time stages obtained in the classical Drucker-Prager model. It may be recommended a detailed and critical assessment of the constitutive model features before using the calculated stress and strain fields to predict the stability of a riverbank. Especially, it has to be pointed out that the omission of the effect of suction from slope stability calculations may yield incorrect predictions.

6. ACKNOWLEDGMENTS

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