Simulation of Hydrological Processes in the Dump Slope of a Mining Pit for Landslide Forecasting

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ABSTRACT

Dump slope in the open-cast mining pit is always a safety issue, as it can experience catastrophic destruction due to the slope failure caused by various factors, such as atmospheric conditions (especially precipitation), vegetation and so on. The precipitation has direct influence on the water content change with the infiltration water into the unsaturated slope especially during the heavy rainfall event. The significant effects of vegetation on the slope stability can be essentially contribute to two major aspects, water movement via the soil-plant-atmosphere continuum and soil reinforcement by the root system. The aim of this study is to investigate the hydrological regime in the dump slopes and the influence of the saturation degree on the stability of dump slopes under the consideration of precipitation and vegetation with the program PCSiWaPro® (by Technical University of Dresden).

Physical model tests of a sand slope at TU Dresden showed that it was the partial saturated condition that had already caused mechanical instabilities. Using the simulation program PCSiWaPro®, the distribution of the water saturation in the partial saturated slope area under transient boundary conditions can be simulated. It is based on solving the RICHARD's Equation in two spatial dimensions using the finite element method. The integration of a weather generator into PCSiWaPro® allows a transient flow calculation with respect to atmospheric conditions (precipitation, evaporation, daily mean temperature and sunshine duration) and removal of water by plant roots and leaves. With PCSiWaPro® a case study in an open-cast mining pit in Saxony (Germany) has been carried out to simulate the hydrological process in the dump slope especially for the unsaturated zone; then with the simulation results, the stability analysis models could be applied to verify how detailed water content and vegetation influence the stability of the dump slope.

Keywords: dump slope, water content, saturation, stability analysis,

INTRODUCTION

This study area locates between Leipzig and Bitterfeld with the City of Delitzsch in the center which has been shaped by the lignite mining activities for more than one century. Mining activities are always essential for the production of necessary minerals and then for the development of the modern society. However they also bring us lots of serious environmental and ecological problems, among which the dump slope landslide in the mining pit is one of the main concerns. Constantly appearing causes have a great weight on the issue of slope stability, like the heavy rainfall event and the change of the ground water level.

Surface erosion (surface runoff) and increase of water saturation in the dump slope body are the main causes of instability risk (Bonelli, 2013). There was an early assumption that the landslides and suffusion phenomenon can arise only in the fully saturated soil areas on the air side; however AIGNER (2004) indicated from a physical experiment (shown in Figure 1) that this can occur even in the partially saturated soil area of the slope. The surface erosion is relatively easy to be detected and avoided, while the soil moisture increase risk cannot be easily identified. Therefore, these geological structures are more sensitive and dangerous due to the flow from the ground water and rainfall water infiltration into the unsaturated zones (Bonelli, 2013).

Figure 1 A physical model slope with slides on the air side (Aigner, 2004)

In those unsaturated slope areas, various factors could influence the water balance and then the stability, for example, soil materials, geometry, atmospheric conditions (e.g. precipitation), and even vegetation (Tien H. Wu, 2013) (see Figure 2). The precipitation has direct influence on the water content change with the infiltration water into the unsaturated slope and then changes groundwater movement regime (especially in an extreme rainfall event). The significant influence of vegetation on slope stability can essentially be attributed to two major aspects: water movement via the soil–plant–atmosphere continuum (SPAC) (Coppin, Barker & Richards, 1990) and soil reinforcement by the root system (Gray, 1995). Vegetation is a major component of SPAC, responsible for the suction force of water against gravity. The absorbed soil water will subsequently be removed through the transpiration process into the atmosphere. Ultimately, this water cycle system would result in less saturated and more stable slopes. Concurrently, vegetation also contributes to mass stability by increasing the soil shear strength through root reinforcement (Gray, 1995). The frequency of slope failures tends to increase when vegetation is cut down and their roots decay (Abe, 1997).

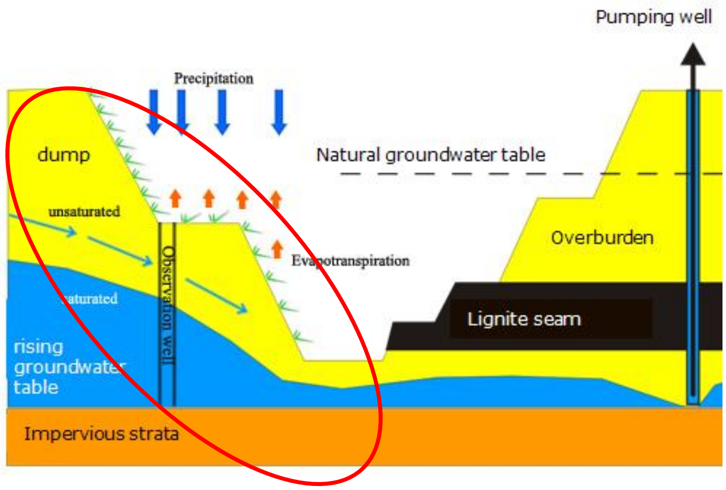

Figure 2 A simplified structure of the dump site

HYDROLOGICAL PROCESS SIMULATION PROGRAM

The hydrological process could be simulated by the Program PCSiWaPro® (developed at the Technical University Dresden, Institute of Waste Management and Contaminated Site Treatment) which could describe the distribution of water saturation under transient boundary conditions (Graeber et al., 2006). With PCSiWaPro® a 2D model of the dam could be built, incorporating information of geometry, soil properties, climate parameters and geohydraulic as well as time-dependent boundary conditions. To determine the effects of the factors mentioned above on the through-flow, water saturation and the geomechanical instabilities in the partially saturated region of the dump slope, the seepage line as the border between the fully saturated and partially saturated zones was used for validating the simulation results.

Theoretical Background of PCSiWaPro®

PCSiWaPro® simulates water flow and contaminant transport processes in variably saturated soils, under both steady-state as well as transient boundary conditions. The flow model can be described by the RICHARDS equation (equation 1).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^A \frac{\partial h}{\partial x_j} + K_{iz}^A\right)\right] - S \qquad (1)$$

The equation contains the volumetric water content θ, pressure head h, spatial coordinates xi (x_1 = x and x_2 = z for vertically-plane simulation), time t, and K_{ij}^A as components of the dimensionless tensor of anisotropy K. S is a source/sink term, which can be partly characterized by the volume of water that is removed from the soil by plant roots. The effects described by this strongly nonlinear partial differential equation are subject to hysteresis, especially the relationship between water content and pressure head. This relationship can be described by the VAN-GENUCHTEN-LUCKNER equation (2).

$$\theta = \theta_r + \frac{\phi - \theta_{r,w} - \theta_{r,l}}{\left[1 + (\alpha h_c)^n\right]^{1-\frac{1}{n}}} \tag{2}$$

Φ is the porosity of the soil; h_c characterizes the pressure head difference between the wetting (water) and non-wetting phase (air); α (scale factor) and n (slope) are empirical VAN-GENUCHTEN parameters (Kemmesies, 1995). The simulation tool PCSiWaPro® implements this relationship and solves the RICHARDS equation in two vertically-plane dimensions with transient boundary conditions, using the numerical finite element approach. For the solution of the linear system of equation originating from discretizing the RICHARDS equation, an iterative preconditioned conjugate gradient solver is used.

Advantage of the Program PCSiWaPro®

There are some advantages of the program PCSiWaPro® in the field of the 2D simulation of hydrological processes. First of all, in PCSiWaPro® four kinds of Pedotransfer functions (Vereecken H. et al., 1989; Weynants, Vereecken & Javaux, 2009; Teepe, Dilling & Beese, 2003; Woesten, Pachepsky & Rawls, 2001) have been applied for the estimation of VAN GENUCHTEN-LUCKNER parameters α and n based of the corn-size-distribution-curves in the program operation interface shown in Figure 3 below.

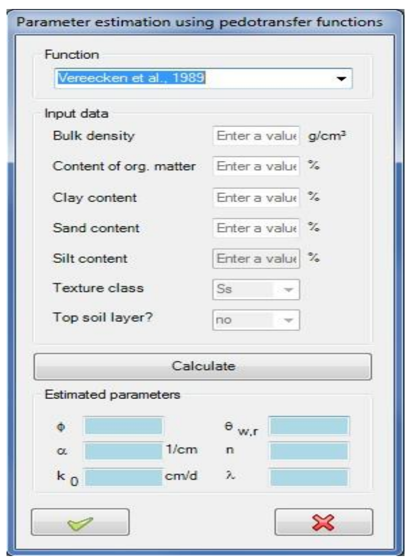

Figure 3 Operation interface of parameter estimation using pedotransfer function in PCSiWaPro®

Secondly, a further advantage of PCSiWaPro® is the coupling of a weather generator whose input data basis is real climatic data with the time frequency of one day, such as precipitation, daily average temperature and sunshine duration from the public weather data of the German Weather Service (DWD) (Figure 4); this generator allows for the generation of transient infiltration fronts with a temporal resolution up until 30 minutes with respect to those atmospheric conditions and removal of water by plant roots. In addition, it can be applied for the unknown location based on the method of the spatial interpolation and the method of the inverse distance with the geographic coordinate of the surrounding climate stations. With these advantages, a much better resolution of the hydrological process simulation could be achieved in the dump slope either during a dry season or during a rainfall event. For example, variation of water content distribution in the slope could be simulated and predicted hourly especially during a wet season for the risk management of the possible landslide. However, when transferring this program to other countries (e.g. Poland, China, and Japan), the DWD data in this weather generator is no more suitable; instead, the local weather service data needs to be transferred to PCSiWaPro® in order to get high resolution time series for the local hydrological simulation work.

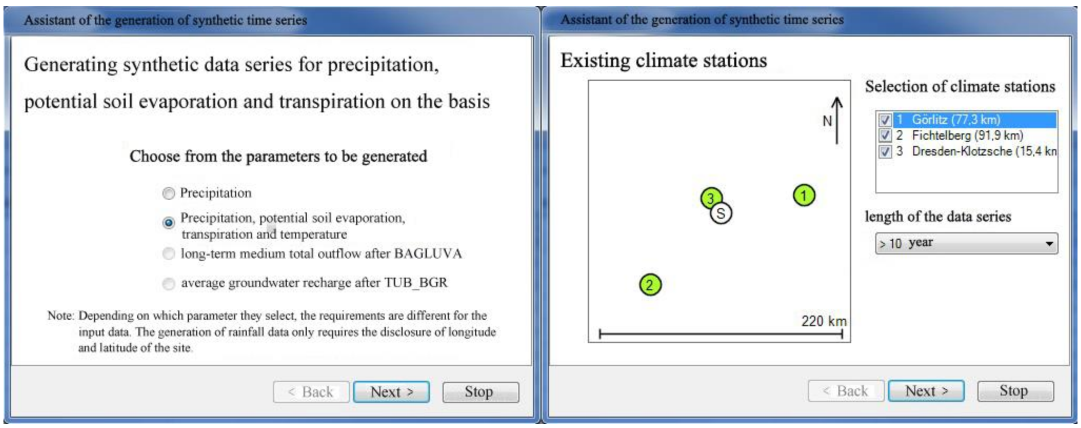

Figure 4 Operation interfaces of the weather generator for an example in the Dresden area

Thirdly, PCSiWaPro is coupled with soil parameter and chemical data bases for the estimation of the VAN GENUCHTEN-LUCKNER soil parameters and the transport parameters, respectively.

Lastly, PCSiWaPro® could provide us a strong calibration system between the simulation results and measured values from any observation point in the dump slope; with the pre-input of the measured data, this program carries out detailed calculation for different kind of values (e.g. pressure head, water content, concentration). This calibration system could also be taken as a test for the applicability and availability of the program PCSiWaPro® in our study area.

STABILITY ANALYSIS MODEL

Slope stability problems of the dump slope are among the most commonly encountered problems in geotechnical engineering. Numerous scientists conducted a large amount of research in this field and several numerical methods were developed for the slope stability analysis. The typical methods are Infinite Slope Equation, Ordinary Method of Slices, JANBU'S Simplified Method, MORGENSTERN-PRICE method and so on. Due to the close relationship between the water content (or saturation) and slope stability, the infinite slope equation is one of the most applicable equations to be used together with water flow simulation in unsaturated slope bodies (Hammond C. et al., 1992; Biondi G. et al., 2000); and it assumes identical conditions occur on any vertical section of the slope. The objective of the analysis is to produce estimates of the probability of infinite slope failure in form of the conventional factor of safety (Fs) which is defined as the ratio of shear strength to shear stress for a one-dimensional infinite slope under both saturated and unsaturated conditions (Griffiths, Huang & Gordon, 2011; Duncan & Wright, 2005; Hammond et al., 1992); equation 3 and 4 are given for the Fs analysis within the root system as,

$$\mathrm{Fs}_{(z)} = \frac{\tan\phi'}{\tan\beta} + \frac{2(c'+c_r)}{rz\sin 2\beta} + \frac{S_e}{rz}(u_a - u_w)(\tan\beta + \cot\beta)\tan\phi'$$

$$\mathrm{Fs}_{(z)} = \frac{\tan\varnothing'}{\tan\beta} + \frac{2(c' + c_r)}{\gamma z \sin 2\beta} + \frac{S_e}{\gamma z}(u_a - u_w)(\tan\beta + \cot\beta)\tan\varnothing' \quad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

where u_w is the pore water pressure; u_a is the pore air pressure; S_e is the saturation; θ is the volumetric water content; θ_r is the residual volumetric water content; θ_s is the saturated volumetric water content; $(u_a - u_w)$ is soil matric suction; z is vertical depth below the ground surface; Ø' is the angle of internal friction; c' is the soil cohesion; β is the slope angle and γ is the total soil and water unit weight (Lu & Godt, 2008); c_r is the root reinforcement (Tien H. Wu, 2013).

From the VAN GENUCHTEN-LUCKNER equation, the relationship between water content and matrix suction can be easily achieved, as shown below (equation 5):

$$u_a - u_w = \frac{\left[\left(\frac{1}{S_e}\right)^{\frac{n}{n-1}} - 1 \right]^{\frac{1}{n}}}{\alpha} \quad (5)$$

α is scaling factor; n is slope factor. α and n could be achieved by the pedotransfer functions in PCSiWaPro®.

The root reinforcement c' should be neglected in equation 3 when the slope depth is below the root area. Generally, when the Fs value of a dump slope is reduced to less than one unit, landslides could be predicted and the necessary prevention is in need to reduce the landslide risk.

In the above three equations (3, 4 and 5), the values of all those parameters could be easily achieved from the local geo-data base except the volumetric water content θ which is variable depending on the local hydrological and atmospheric conditions. However, θ could be calculated or predicted by the program PCSiWaPro®.

DISCUSSION OF SIMULATION RESULTS

A real dump slope model has been selected from the mining area near the city of Leipzig for the practical application of the program PCSiWaPro® whose simulation results would play one of the key roles on the stability analysis. This study structure is totally 300m wide and 94m high with horizontally layered dump soils (e.g. 20m depth of clay layer in the middle with the hydraulic conductivity k_f of 10^{-8} m/s, 11m depth of sandy cover with the k_f value of $1.3 \cdot 10^{-5}$ m/s over the clay layer) and sandy slope with the k_f value of $4.5 \cdot 10^{-5}$ m/s. Additional basic data, like groundwater water level change, have been obtained from the local agency and the company IBGW Leipzig.

After setup of the model in the program PCSiWaPro®, a simulation period of five years from Jan. 2000 to Jan. 2005 was selected. On the dump slope, atmospheric boundary condition has been defined, which means this slope would have additional input of rainfall water; after the formation of this dump slope, a constant groundwater level of 88m was detected during this simulation period, which supports the determination of the boundary condition of constant potential head on the left side of this model.

In order to better investigate the contribution of precipitation to the increase of water saturation in the slope and groundwater table, a simulation without input of rainfall water has been shown beforehand in Figure 5 which displays the saturation condition in different soil layers in this slope for the day of 30th June 2004. In the zoomed figure, the moderate increase of groundwater surface could be explained by the increasing capillary rise of water in the slope sand from the saturated clay soil which exhibits much higher water retention due to the much smaller particle size. Accordingly in Figure 6 the different blue colors below the groundwater surface indicate the different saturated water content of different dump materials; due to the larger porosity, the clay material with the darker blue color shows the higher saturated water content (0.52) compared with the sandy slope showing the lower water content (0.4). In addition, in PCSiWaPro® the implemented mesh generator for calculation depending on the finite element method uses the "Boundary Representation Modelling Technique" and therefore requires the specification of the model boundaries; in this simulation the structure of the model was discretized with medium finer (0.5 m) meshes, which results in a good representation of water content distribution. However the serrated lines between two different water content and water saturation layers could be even more smoothed with finer model structure meshes (e.g. 0.1 m).

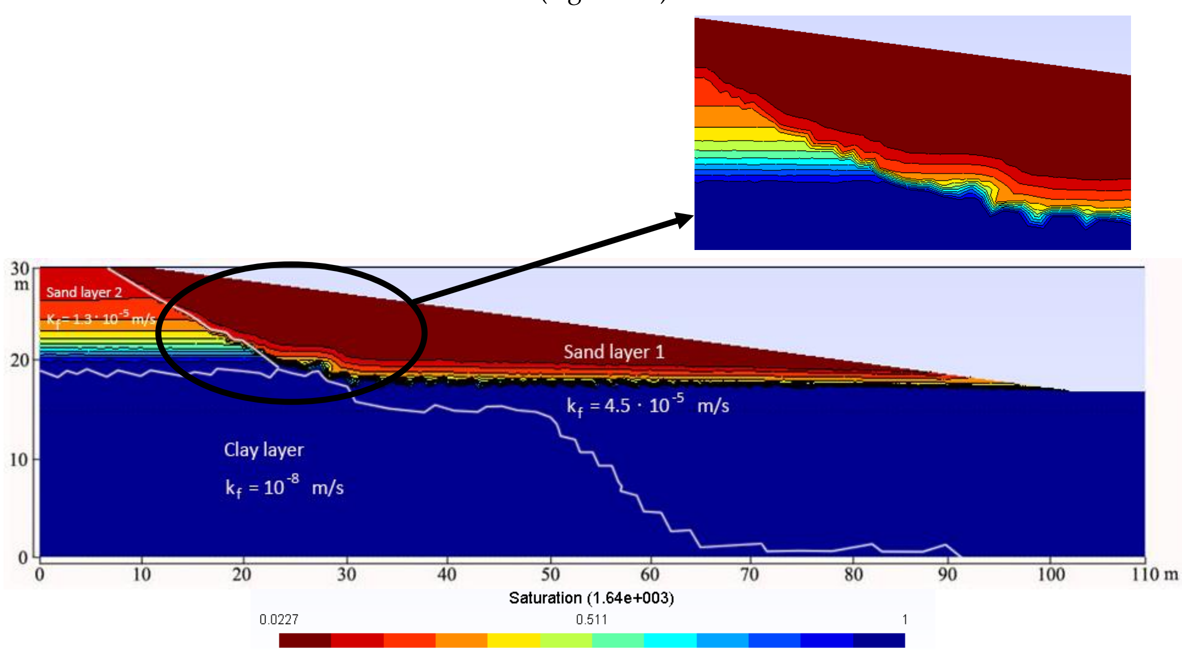

Figure 5 Water saturation simulation without input of precipitation on June 30th, 2004 (the white lines are the borders of different soil layers with different hydraulic conductivity)

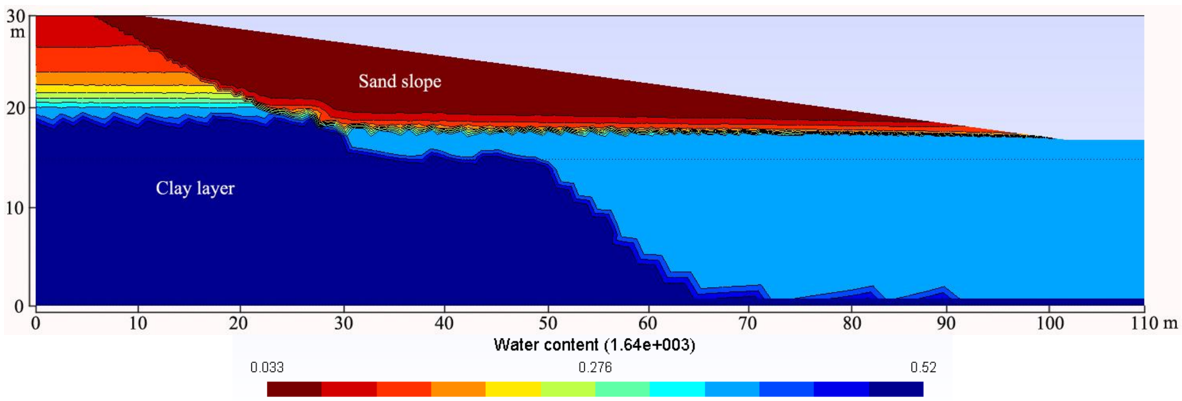

Figure 6 Water content simulation results without input of precipitation on June 30th, 2004

Figure 7 shows the precipitation data output from the weather generator in PCSiWaPro® for a typical year in the study area. As can been seen in this graph, the rainfall event mainly occurred in the summer between June and September, especially in the mid-June, early July and early September. In addition, although the rainfall season came every year from the mid-June, the ground-water level showed no change between the year of 2000 and 2005, which was mainly due to the manmade operation of pumping discharge from the groundwater during the mining activities in order to prevent the possible overload groundwater storage especially in the rainfall season and to prevent the possible geological and environmental disasters.

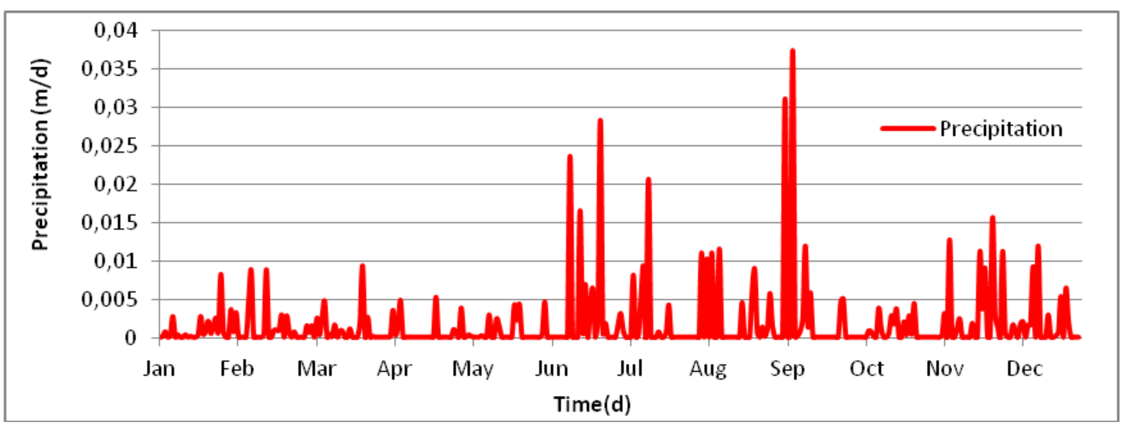

Figure 7 Typical daily precipitation data for one year in this area from the weather generator in PCSiWaPro®

Depending on the advantage of weather generator, the simulation result of water content was illustrated in Figure 8 for 30th June 2004 (during the rainfall season) considering both the groundwater flow and rainfall water infiltration. Rainfall water provided an additional flow into the top and the right sand slope embankment, thereby increasing water content in this unsaturated slope. In addition, the rainfall water reaching the groundwater table in the slope has also performed as a complementary for the groundwater recharge.

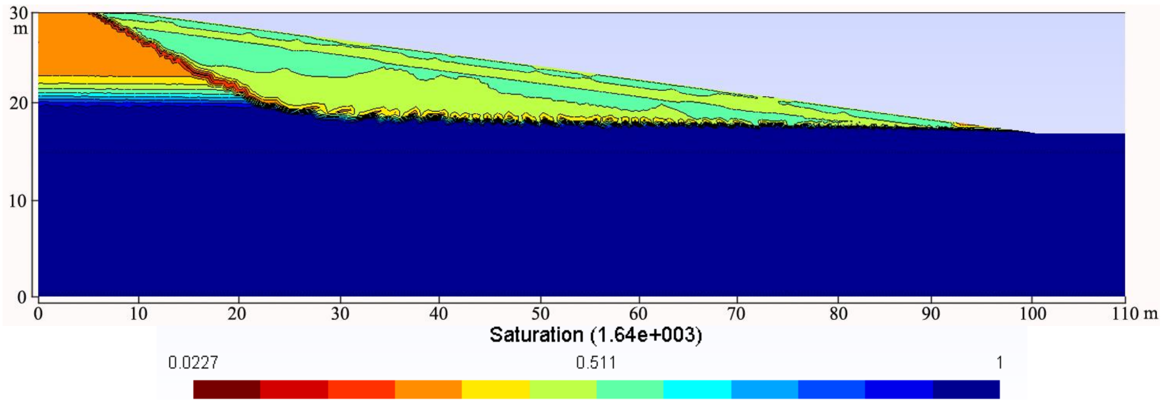

Figure 8 Simulation of water saturation distribution with input of precipitation on June 30th, 2004

In addition, due to the constant groundwater table after the year 2000, a stable value was achieved for the water level measurement from an observation well in this dump slope. A comparison between the measured and simulated water level has been carried out. The accordance between the measured and the computed values using the program PCSiWaPro® was good for our study area. However only a little bit deviation (0.3m) found in the comparison could be explained by the fact that our simulation was mainly based on the average values of those different dump soil parameters (e.g. average porosity, hydraulic conductivity); however the accuracy of the simulation could be improved with more field and laboratory investigation for soil parameters of the different dump slope soils.

CONCLUSIONS

1) The experiment results from the physical slope model in the laboratory indicated clearly that ground water flow had been already detected in the highly partial-saturated slope body; and due to the increasing of water saturation, the stability of this unsaturated slope was influenced with an already-happening surficial landslide.
2) With the Program PCSiWaPro®, water content and saturation distribution in the slope zone could be simulated and predicted dynamically within the whole study period, which is the preliminary work for stability analysis by the infinite slope model.
3) This study has also tested and calibrated the availability of PCSiWaPro® to simulate the groundwater level variation in an observation well within a continuous period.
4) The agreement between the measured groundwater level and the computed one using the program PCSiWaPro® was good for our study area; however there was a little deviation between those two values. These deviations could be caused by poorly estimated soil parameters (e.g. porosity, hydraulic conductivity).
5) With the simulation results, the stability analysis has been carried out and certified that this dump slope was stable (the minimum Fs value is 3, and the detailed calculation is not exhibited here); although the precipitation has contributed a lot for the decrease of the slope

stability, due to the manmade operation the groundwater table in this dump slope was always kept stably low between the year of 2000 and 2004, which resulted in a safe slope.

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