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Hydrological Process Analysis in Earth Dams Using the PCSiWaPro® as a Basis for Stability Analysis

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Abstract: Earth dam is always a safety issue, as it can experience catastrophic destruction due to the slope failure caused by various factors, such as water content increasing in earth slopes, vegetation root decay and so on. This study is to investigate the variation of hydrological processes in the saturated and partially saturated slopes with a new simulation program PCSiWaPro® (a computer aided leachate forecast tool) under transient boundary conditions. The integration of a weather generator inside the PCSiWaPro® allows a transient water flow calculation with respect to atmospheric conditions (precipitation, daily mean temperature and sunshine duration) and removal of water by plant roots and leaves. The simulation results of one scenario in a Chinese earth dam clearly demonstrate a good applicability of the program PCSiWaPro®.

Key words: Earth dam, water balance, seepage line, vegetation, precipitation.

1. Introduction

An earth dam is one kind of hydraulic construction structures built with highly compacted earth and used for the purpose of flood control [1]. However, severe flood events occur every year due to the dam collapse, for example, the flood caused by the Elbe River in 2002 [2] and in Fischbeck in July 2013 [3].

Surface erosion (surface overflow) and increase of water saturation in the dam body are the main causes of dam instability [4]. There was an early assumption that the landslides and suffusion phenomenon arose only in fully saturated soil areas on the air side; however Aigner [5] showed by physical experiments that dam instability occurred even in the partially saturated soil area. The surface erosion is relatively easy to be detected and avoided, while the soil moisture increase risk cannot be obviously identified. Therefore, those hydraulic structures are more dangerous due to ground water flow and rainfall water infiltration into the unsaturated zones [4].

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In an unsaturated earth slope, various factors can influence water balance and then the stability, for example, construction methods, soil materials, geometry, atmospheric conditions (e.g. precipitation), and vegetation [6] (Fig. 1). Precipitation causes water level to increase in the reservoir and river which dives the rising movement of the seepage line in the dam body. In addition, precipitation has direct influence on water content change with infiltrated rainfall water into the unsaturated slope especially in an extreme rainfall event. The significant influence of vegetation can be attributed to one major aspect: water movement via the SPAC (soil—plant—atmosphere continuum) [7]. Vegetation is a major component of SPAC, responsible for the suction force of water against gravity. By absorbing parts of soil water, plants thus play a significant role in drying the slopes [8]. That absorbed soil water is subsequently removed through the transpiration process into the atmosphere [7]. Ultimately, the water cycle system results in less saturated and more stable slopes. The frequency of slope failures tends to increase when vegetation is cut down [9].

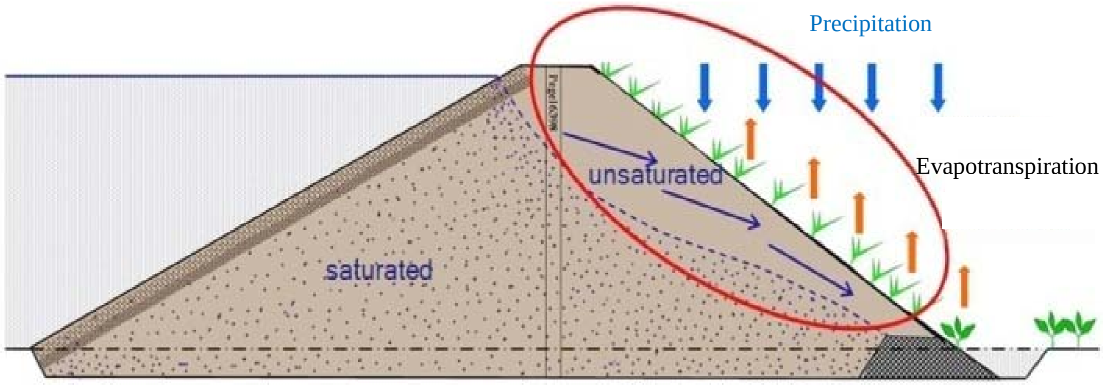

Fig. 1 Water balance in the saturated and partially saturated region in an earth dam [10].

2. Methodologies

2.1 Hydrological Simulation Program PCSiWaPro®

The hydrological processes can be simulated by the Program PCSiWaPro® which was developed in the Institute of Waste Management and Circular Economy at the Technical University Dresden. This program has been adapted to several languages (German, English, Spanish, French, Polish, Japanese, Vietnamese, Arabic).

2.1.1 Mathematical Background of the PCSiWaPro®

PCSiWaPro® simulates water flow as well as solute transport in variably saturated soils under both steady state and transient boundary conditions [11]. The flow model in the program is described by the Richards equation, see Eq. (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, hydraulic head h, spatial coordinates x_i ($x_1 = x$ and $x_2 = z$ for vertically-plane simulation), time t, and K_{ij}^{A} as components of the dimensionless tensor of anisotropy of K. S is a source/sink term, which can be partly characterized by the volume of water that is removed from the soil by vegetation roots. The PCSiWaPro® solves the Richards equation in two vertically-plane dimensions using a finite element approach and the Galerkin-method [10]. The effects described by this strongly nonlinear partial differential equation are subject to hysteresis, especially the relationship between water content and pressure head [10]. This relationship is described by the Van-Genuchten-Luckner equation, see Eq. (2).

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

where Φ is soil porosity; θ_r is residual water content; $\theta_{r,1}$ is residual air content; 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 [12] and can be either estimated by the Perdotransfer Functions in the program or measured directly in the laboratory.

2.1.2 Advantages of the PCSiWaPro®

When compared with some well-known programs for the hydrological process simulation, for example HYDRUS and FEFLOW, the program PCSiWaPro® does have two main advantages.

On the one hand, an attractive advantage of the PCSiWaPro® is the integration of a weather generator whose synthetic time series are derived from the German Weather Service (DWD) [10]. Based on the statistical Markov chain analysis, this generator allows a generation of transient flow calculation with respect to different atmospheric conditions, i.e. precipitation, daily mean temperature and sunshine duration [13]. In addition, it is available for all unknown locations based on the spatial interpolation method and the inverse distance method with the recorded data of surrounding climate stations (Fig. 2). Furthermore, by the weather generator the potential evapotranspiration on the site is easily calculated by the method of Turc-Wendling and the input of different site parameters like top surface soil types, site inclination and orientation, land-use forms, vegetation covers (Fig. 2). Within the generator the interception and transpiration data can be as well clearly illustrated and exported from the program for other hydrological analysis.

On the other hand, PCSiWaPro® provides a strong calibration system between the measured and simulated results for the whole model area. After pre-definition of observation points in the input system, this program carries out detailed calculation for different values (e.g. pressure head, water content, saturation); calculation results for all observation points can be looked through in an output data sheet corresponding to each simulation time step.

With PCSiWaPro® a 2D model of an earth dam can be built, incorporating information of geometry, soil properties, climate parameters, geohydraulic and time-dependent boundary conditions. In addition, to verify the applicability of the program, measured groundwater levels at observation points in the dam body are compared with simulated values in the model.

2.2 Stability Analysis Model

Slope stability problems are one of the most popularly encountered problems in geotechnical engineering. Since now lots of researches about the stability analysis for dam and dike slopes have been carried out by the geoscientists, and several applicable methodologies have been put forward, like the infinite slope analysis model and the limit equilibrium models based on the typical Mohr-Coulomb Model to express the safety of factor in the earth slopes. In this study, only the infinite slope model was applied and discussed for the earth dam stability analysis together with water flow simulation in unsaturated slope bodies. The infinite slope analysis assumes that identical conditions occur on all vertical sections of the slope. The objective of the analysis is to estimate the probability of infinite slope failures in the form of the conventional Fs (factor of safety) which is defined as the ratio of shear strength to shear stress for a one-dimensional infinite slope under both saturated and unsaturated conditions [14-16]; Eqs. 3 and 4 are given for the Fs analysis within the root system as:

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

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

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; ∅' 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 [17]; c_r is the root reinforcement [6] and is neglected when the slope depth is larger than the root system in the slope.

The relationship between water content and matrix suction can be achieved from the Van Genuchten-Luckner equation, see Eq. (5):

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

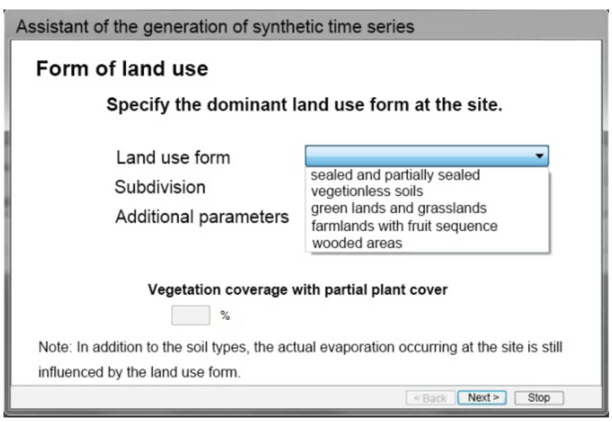

Fig. 2 Interfaces of the weather generator in the PCSiWaPro®.

where α is scaling factor; *n* is slope factor. α and *n* can be either achieved by the pedotransfer functions in the PCSiWaPro® or directly measured in the laboratory.

In Eqs. 3-5, the values of all those parameters can be easily achieved from the local geo-data base except the volumetric water content which varies from different local hydrological and atmospheric conditions; however water content is calculated and predicted by the program PCSiWaPro®. Generally, when the Fs value in a dam slope is less than one unit, landslides can be predicted and the necessary prevention is in need to reduce the landslide risk.

3. Results and Discussion

A real earth dam has been investigated in China for the practical application of the PCSiWaPro®; the earth dam has 600-meter width and 86-meter height. Additional site data, i.e. precipitation, and water level change in the reservoir, have been obtained from the local agencies. This earth dam contains three main parts, two cores with slightly sandy clay and the rest dam body with silty sand. As there were no available data collected for the Van Genuchten parameters of the soils, the estimated values were applied from the Program PCSiWaPro®.

Firstly, after the setup of the dam model in the PCSiWaPro®, the air-side dam slope was defined with an atmospheric boundary condition, which meant that this slope was influenced by the infiltrated rainwater. The daily precipitation data and water level changes in the reservoir in the year 2012 were input into the PCSiWaPro® for the hydrological simulation. Depending on the advantages of the Program PCSiWaPro®, the effects of evapotranspiration at the air-side dam slope were generated and as well input into the model system. In order to study the influence of precipitation on the unsaturated slope, a wet day on 20th June with a daily rainfall of 70 mm has been selected for detailed simulation analysis and the simulation results of water content distribution are displayed in Fig. 3. In the saturated areas, the two clay cores show higher saturated water content with a color of dark blue than the other saturated parts of the dam, which is due to the different soil porosities; the higher the soil porosity is, the larger the saturated soil water content will be. The zoom, in image in Fig. 3 describes

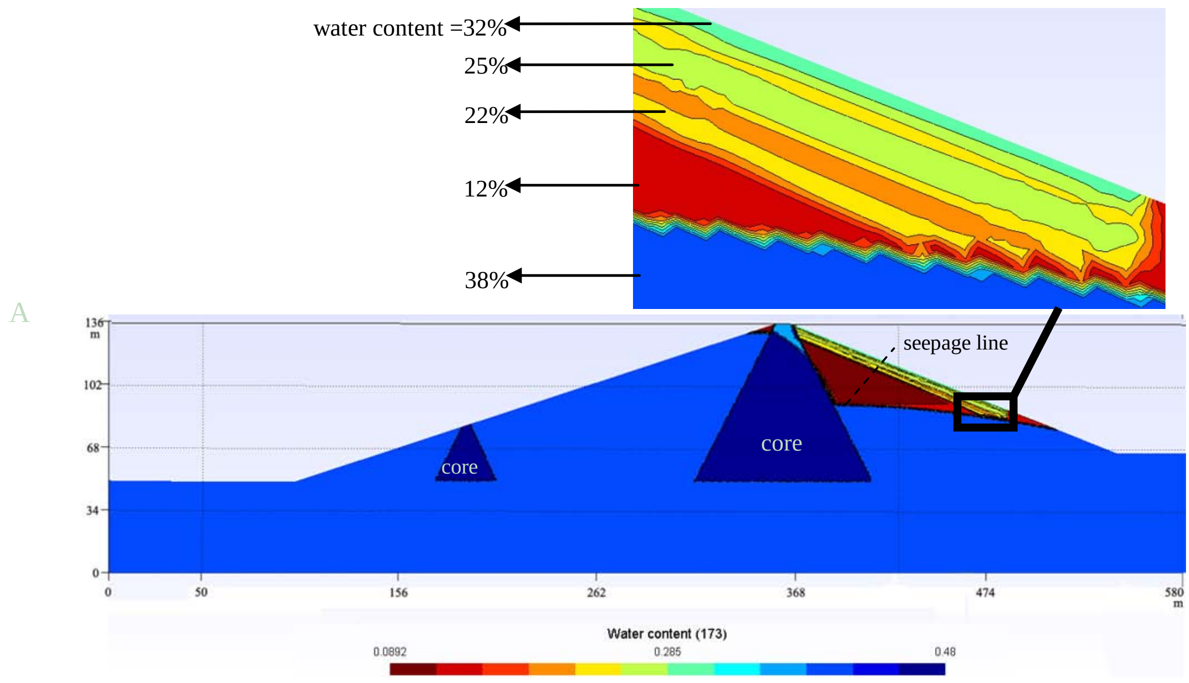

Fig. 3 Water content simulation from PCSiWaPro® with wet weather on June 20th, 2012.

the detailed distribution of water content from 12% to 32% near the seepage line in those unsaturated zones; the surface layer of the slope was influenced by the infiltrated water with a slim aqueous strip with a color of light green.

Secondly, in order to better investigate how the precipitation influenced the unsaturated slope, the simulation result of water content on June 29th was selected with dry weather. The detailed effect of infiltrated rainfall water on different layers of the unsaturated slope was represented in Fig. 4 and Table 1 with a comparison between two cases with different weather conditions. The heavy rainfall event on 20th June increased water content to 32% in the top surface layers (0-1 m) of the slope; then after nine days' evaporation, the top surface got much drier and water content decreased to only 12%. However in the deeper layers (> 8 m) there was no clear difference of water content being detected between two cases. From this fact, it can be concluded that water content on the slope subsurface was much more sensitive to the atmospheric conditions than that in the deeper layers.

Finally, to test the applicability of the program PCSiWaPro®, a comparison was carried out between the measured and simulated water levels at two observation points, one in a clay core and the other in the sandy slope (Fig. 5). The groundwater levels were measured every two weeks for nine months by piezometers.

The comparison for both observation points is illustrated in Figs. 6 and 7. By the RMSE (root mean squared error) analysis, the simulation results at both points had a nice fitness with the measured data. However, a little bit deviation has been clearly found between simulated and measured values for water level in the sandy slope between April and June (Fig. 7). That deviation was explained by the fact that the simulation was mainly based on the soil data DIN 4220 and not on the exact soil parameter investigation in China. Last but not least, due to the man-made operation

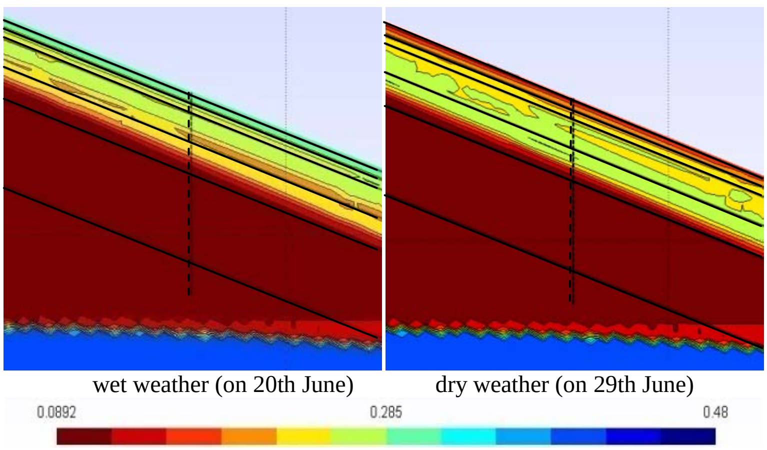

Fig. 4 Water content distribution in the unsaturated slope during the wet and dry weather.

Table 1 Comparison of water content at different depths during the wet and dry weather.

Depth in the unsaturated slope (at the air side, m)	Water content θ in different layers on two days	
	June 20th, 2012 Wet weather	June 29th, 2012 Dry weather
0.2	0.32	0.12
1.0	0.25	0.18
2.0	0.25	0.22
6.0	0.22	0.25
9.0	0.09	0.09
18.0	0.09	0.09

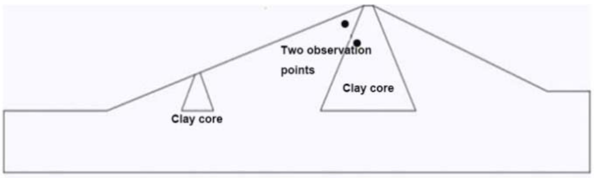

Fig. 5 Position of two observation points in the Chinese earth dam.

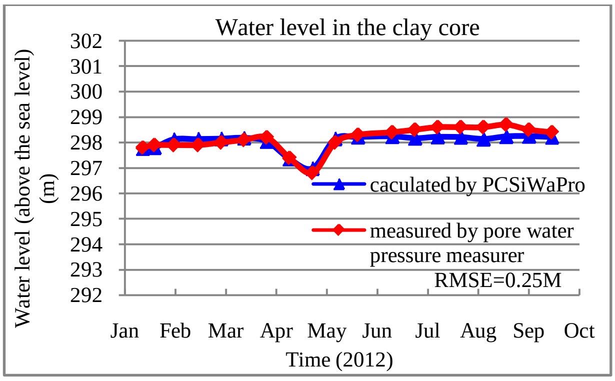

Fig. 6 Comparison between the computed and measured water levels at an observation point in the core.

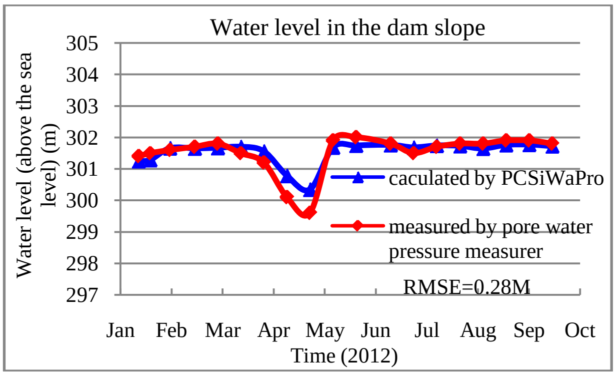

Fig. 7 Comparison between the computed and measured water levels at an observation point in the slope.

of water storage release in the reservoir from the middle March to the middle April, both figures exhibited a uniform decrease of water level during the same period. And the more moderate decrease of water level in the clay core can be explained by the larger hysteresis effect of the clay soil with the smaller hydraulic conductivity and pore space diameter.

4. Conclusions

Earth dam slope instability is a major concern in China where slope failures have caused catastrophic destruction on surrounding areas. The slope stability might be determined by various external and internal factors which result in the imbalance of forces inside the slope. The external factors include the external loading force, e.g. the human activities and large plants on the slope; while the internal triggering factors mainly refer to the internal changes like variation of hydrological processes in the earth slope;the hydrological processes in the earth slope in one scenario have been simulated by the program PCSiWaPro® in this study; some experiences based on the application of the Program PCSiWaPro® are listed below:

(1) By the program PCSiWaPro®, water content distribution in slopes can be simulated and predicted dynamically in the whole period, which is the preliminary work for slope stability analysis by the infinite slope model.

(2) The strong calibration system inside the PCSiWaPro® is favorably applicable and convenient to compare the measurement and simulation results for every point in the model.

(3) The study in a Chinese earth dam proved the high availability of PCSiWaPro® to simulate and predict groundwater level variations at observation points.

(4) However, there was only a little bit deviation being found between the measured groundwater levels and the computed ones using the PCSiWaPro®. The deviation was caused by poorly estimated soil parameters (e.g. porosity, hydraulic conductivity) which were based on the given DIN 4220 data.

(5) More investigation work for soil parameters in China is in great need in order to better match between the PCSiWaPro® simulation and real observation.

(6) With the simulation results, stability analysis was carried out and certified that the Chinese earth dam was in stable with a minimum Fs value of 1.7. Although the precipitation contributed a lot to decreasing the slope stability, with the manmade operation the groundwater table at the air side of the dam body was always kept low, which resulted in a safe slope.

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