MODELLING THE FLOW PROCESSES IN UNSATURATED POROUS MEDIA FOR PREDICTING THE WATER CONTENT DISTRIBUTION IN LEVEES AND EARTH DAMS

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Abstract

Levees and earth dams play an important role as flooding protection systems in Germany. The construction and used materials define the stability of a levee or earth dam. To assess the stability and to perform possible measures, knowledge of the geo-hydraulic properties of the levee is necessary. Therefore, it is not sufficient to have information only about the flow processes within the fully saturated part of the levee or earth dam. Moreover, the unsaturated regions are also important because instabilities on the downstream face can occur already at partial saturation. The simulation software SiWaPro DSS, which was developed by the authors, is able to describe the geo-hydraulic processes in both the fully and partly saturated zone in a closed form. Several physical experiments at model-scale dikes with different constructions were performed at the TU Dresden. The program SiWaPro DSS was used to model and simulate these physicals experiments. The basic numerical method and hydraulic model is described, the model setup including boundary conditions as well. Furthermore, a transient boundary condition was implemented to allow for the simulation of fluctuating flooding waves with increasing and decreasing water levels on the water-side. Their effects on the water balance are analysed in that paper and an outlook to further possible improvements is given.

Keywords: Unsaturated flow modelling, transient dike simulation, Richard's equation

René Blankenburg's biography

René Blankenburg studied Geodesy at the Technische Universität Dresden, Germany and obtained his degree in 2004. Since he moved to the Institute of Waste Management and Contaminated Site Treatment, René Blankenburg is attended to the development of numerical simulation software for transient water flow and solute transport in variably-saturated porous media using the Finite Elements Method.

1 Introduction

During the last centuries, in Germany dikes were installed as flooding protection system along river beds. E.g., in the federal state of Saxony, there are more than 500 km of levee systems. In most cases, these sites are grown historically and consist of an inhomogeneous and often unknown construction. Therefore, they do not fulfil the stability requirements of modern levee constructions. Especially in longer flooding periods, the hazard of collapse of the levee because of wetting increases. If seepage water leaves the dike on the downstream side, lifting forces can lead to slope failures of the dike. To estimate the stability of a levee or an earth dam, traditionally the seepage line (level of free water table) is computed using a groundwater simulation tool. This approach implies two disadvantages. First, only the fully saturated part of the dike body can be calculated and no information for the partly saturated region is available. Second, the seepage line can be computed only in an iterative manner which finally leads to approximated solutions. However, mechanical instabilities on the downstream face of dikes may appear even if this zone is not fully saturated. In case of flooding waves with temporal increasing and decreasing water levels, hysteretic effects should be considered as well.

2 Mathematical background

The flow process in variably saturated porous media can be described using the Richard's equation (1) which is able to consider both the unsaturated and fully saturated regions simultaneously.

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

With θ as the volumetric water content, x_i are the spatial coordinates (x, y, z), h is the capillary pressure head, t is the time, K_{ij}^{A} and K_{iz}^{A} are the components of the dimensionless anisotropy tensor $\mathbf{K}$ und K is the function of the unsaturated hydraulic conductivity. The variable S represents the sink or source term and is considered here as the amount of water which is removed by plant roots. Since the pressure head is a dependent variable and both the hydraulic conductivity and the water content on the other hand depend on the pressure head, the Richard's equation is highly non-linear. Therefore, the solution process has to be conducted in an iterative manner.

2.1 Soil hydraulic model

The water content in the medium depends on the capillary pressure head in the pores and can be described using equation (2) [1].

$$\theta_b = A + \frac{\phi - A - B}{\left[1 + \left(\alpha \cdot p_{c,b-nb}\right)^{n}\right]^{1-\frac{1}{n}}} \qquad (2)$$

Where A is the function of the residual water content, B the function of the residual air content, Φ is the porosity of the medium (soil), $p_{c,b\text{-}nb}$ is the difference in the capillary pressure head between wetting (water) and drying (air) phase. The empirical parameters α (scale parameter) and n (slope parameter) were primarily introduced by van Genuchten [2]. In [3] the hysteresis (related to the wetting and drying process of the porous medium) of the state function (2) was investigated and different curves were indicated. The primary draining curve (PDC) shows the situation when the whole pore volume is filled with the wetting phase (water) and the non-wetting phase (air) is not present. The starting point is at pc = 0 cm. The main draining curve (MDC) represents the condition of the pore system when the non-wetting phase exists with a certain phase content θ_{nb}. The starting point of this curve is also at p_c = 0 cm. Both curves (PDC and MDC) show the situation when the wetting phase is leaving the pore volume and is replaced by the non-wetting phase. The main wetting curve (MWC) starts at $p_c = \infty$ and represents the advancement of the wetting phase in the pore space, replacing the non-wetting phase. Fig. 1 shows as graphical illustration of the above described 3 curves. Note the relative large difference between the MDC and MWC of the water content for capillary pressure heads greater 20 cm.

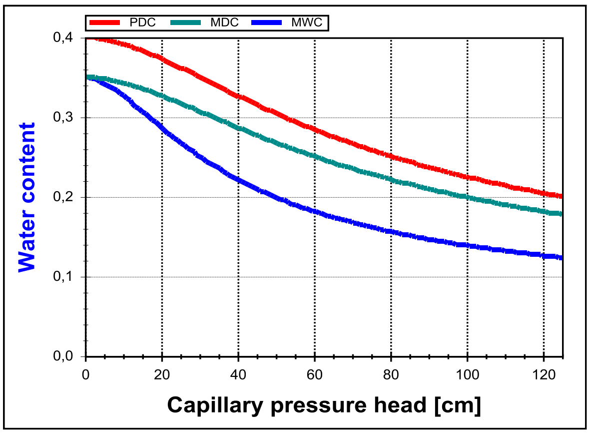

Fig. 1 Drying and wetting curves of a porous medium: PDC - primary draining curve, MDC - main draining curve, MWC - main wetting curve (see text for details)

The consideration of this hysteresis and their effects on the water content enable the complex simulation of fluctuating flooding waves. During these periods, the water content within the levee body is changing. In connection with a decreasing flooding level the saturation inside the levee body remains higher and the hydraulic conductivity as well. Therefore, at the next increasing flooding wave the levee body still has high water content and resulting lifting forces may occur earlier.

2.2 Numerical solution approach

The simulation software SiWaPro DSS which was developed at the Technische Universität Dresden, Institute of Waste Management and Contaminated Site Treatment in cooperation with the KP Ingenieurgesellschaft, implements that approach. The software is able to simulate transient problems in a 2-dimensional, vertical plane and solves equation (1) numerically using the Finite Element method (Galerkin approach with linear basis functions) and the essential specification of boundary and initial conditions. The resulting system of linear equations is solved with an iterative preconditioned conjugated gradient method [4]. The preconditioning is conducted with using incomplete LU decomposition. Due to the strong nonlinearity of equation (1), short time steps are required (especially in presence of fine grained soil types as clay or loam) and result, in combination with large amount of iterations per time step, in high computing times. Parallelization of both the matrix-construction-process and the solver can help to reduce the simulation runtime and to use the computing power of modern multi-core CPU's (several cores on one processor die) more efficiently. Since the simulation kernel of the software is written in FORTRAN language, compiler directives for the OpenMP API standard [10] were used to parallelize loops according to the fork-join model. OpenMP uses threads to distribute the work among the available cores. Especially for loops over grid-nodes and mesh-elements where each cycle is independent from others, the usage of that programming model is very convenient. The OpenMP execution model is intended to be used on shared memory systems, as represented by current multi-core or multiple-processor (2, 4 or 8-way) machines. The main advantage of that approach is the "step-by-step" parallelization of available simulation software without the need to rewrite large parts of the source code. Since the construction of threads during simulation run needs time, the benefit of using OpenMP increases with the increasing number of loop cycles and the work to have done for every thread within each cycle.

3 Model setup

In [5] several physical experiments with model-scale levees are described. They consist of different construction setups, where the most complex levee is most suitable for longer influence of a flooding. The foot width of the model-scale levee is 3.38 m, the slope angle of 1:2 according to a height of 0.77 m. At the crest of dike a rubber wall is installed which has an anchoring depth of 100% of the levee height. Below the levee a berm with a height of 0.30 m was added at both the water and valley side of the levee to allow for exchange of the inflowing water with the groundwater. On the downstream face, a drainage tube was implemented to effectively discharge excess water (see also Fig. 2). The material of the levee consists of homogenous soil with a grain size ranging from 0.06 to 2 mm and a saturated hydraulic conductivity of $k_f = 3 \cdot 10^{-4}$ m/s. This corresponds to a medium or fine-grained sandy soil.

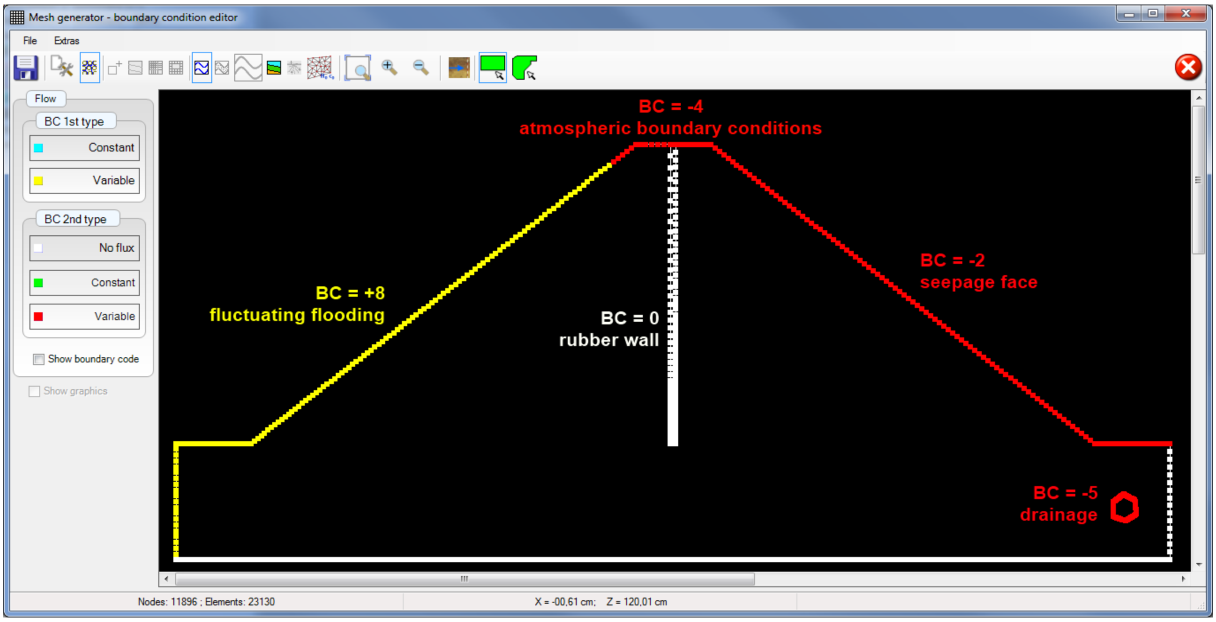

Fig. 2 - Construction of the levee and local assignment of boundary conditions

3.1 Initial and boundary conditions

For the numerical solution of equation (1) initial and boundary conditions have to be provided (for their location see Fig. 2). In the model they are arranged according to the physical experiments described in (1). Table 1 gives an overview about the used boundary condition types and their relevance during the simulation runtime.

Table 1 Coding of the boundary conditions

BC	Relevance for the simulation
+8	Boundary condition of 1st type, variable: pressure head is defined but can change over time: height of the flooding at water side is given during simulation
0	Boundary condition of 2nd type, constant: no-flow boundary condition, used for the rubber wall implemented in the levee
-2	Boundary condition of 2nd type, variable: seepage face, initially unsaturated, water can leave the domain here only if soil is fully saturated in that part: water leaves the model domain on valley side if seepage line reaches that part
-4	Boundary condition of 2nd type, variable: atmospheric boundary condition: precipitation, transpiration by plant roots and soil evaporation can be defined in any desired temporal resolution
-5	Boundary condition of 2nd type, variable: drainage boundary condition, water can leave the domain; if soil is fully saturated, it is switched to a 1st type boundary condition and the pressure head is being hold

The chronological sequence of boundary condition +8 (flooding level) is shown in Fig. 3. It represents a flooding with a low raise (until 200 minutes) and a short tailing (until 230 minutes), followed by a longer flooding wave. During the simulation run, the value at the boundary condition is interpolated linearly by the software between two given points in time to avoid jumping infiltration rates which could lead steep infiltration rates and therefore to numerical oscillations.

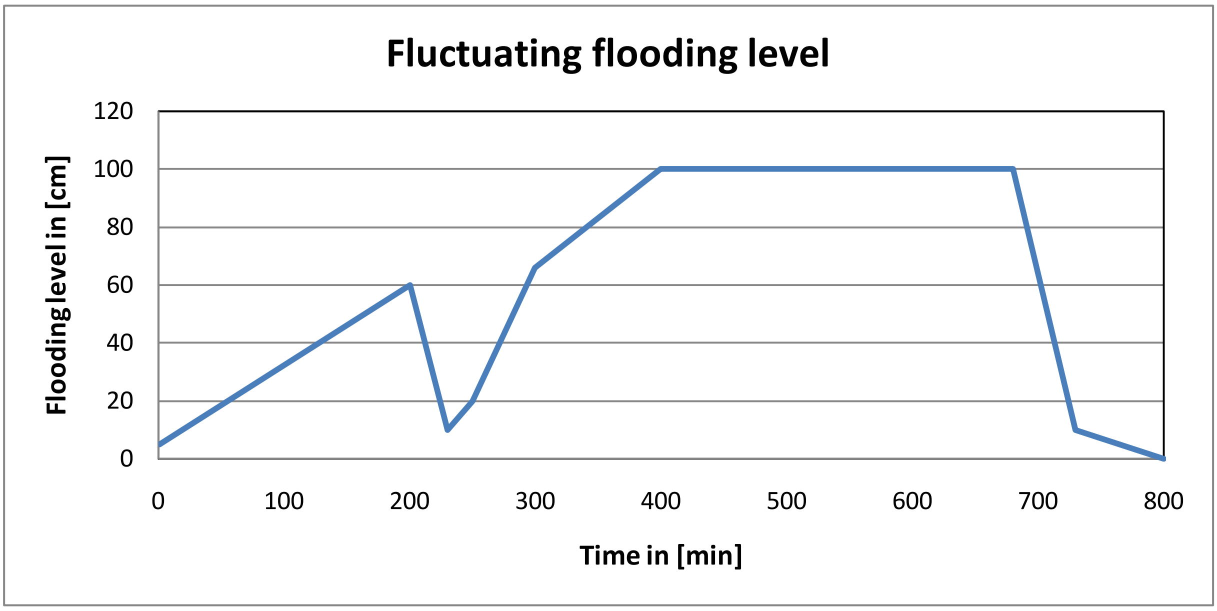

Fig. 3 - Chronological sequence of the flooding level

4 Simulation results

For an adequate analysis of the simulation results, a balancing over the boundary condition fluxes should be accomplished. In Fig. 4 the results of all boundary fluxes with values <> 0 are drawn. Therefore, no graph is shown for the seepage faces (BC -2) because this area is not fully saturated during simulation runtime.

As it can be seen from Fig. 4, the drainage (BC -5) seems to work properly in this simulation. The water is leaving the model domain through it after 350 minutes model time. Until that time, the pore system of the levee body is being filled with the water from the flooding. A peak of the second flooding wave can be observed, but the plateau (as in Fig. 3) is lower (and retarded) due to the water leaving the model through the drainage.

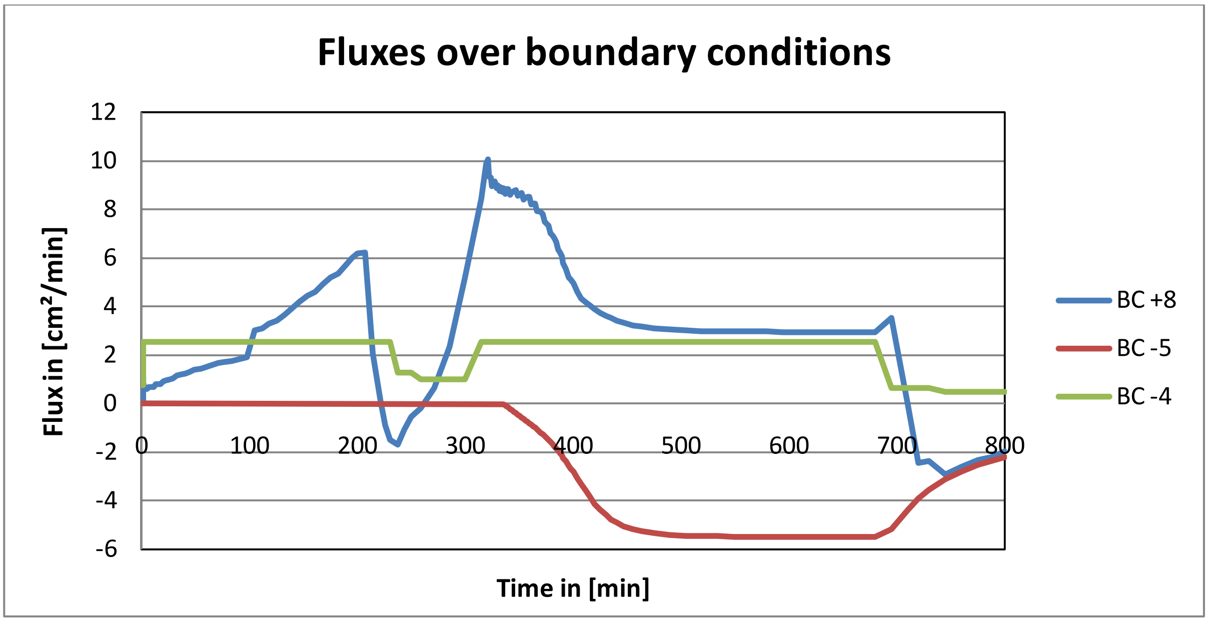

Fig. 4 - Volume fluxes over boundaries where flux <> 0; < 0 means leaving the model domain, > 0 means water flow into the model domain

In Fig. 5 the water saturation distribution within the levee body at time = 650 minutes is presented. Due to the peak of the flooding wave, holding up from 400 to 700 minutes, the situation of the water flow can be considered as steady-state. As it can be seen from Fig. 5, the water saturation reaches almost the valley side (represented by a seepage face boundary condition) but no water leaves the model domain throughout the simulation.

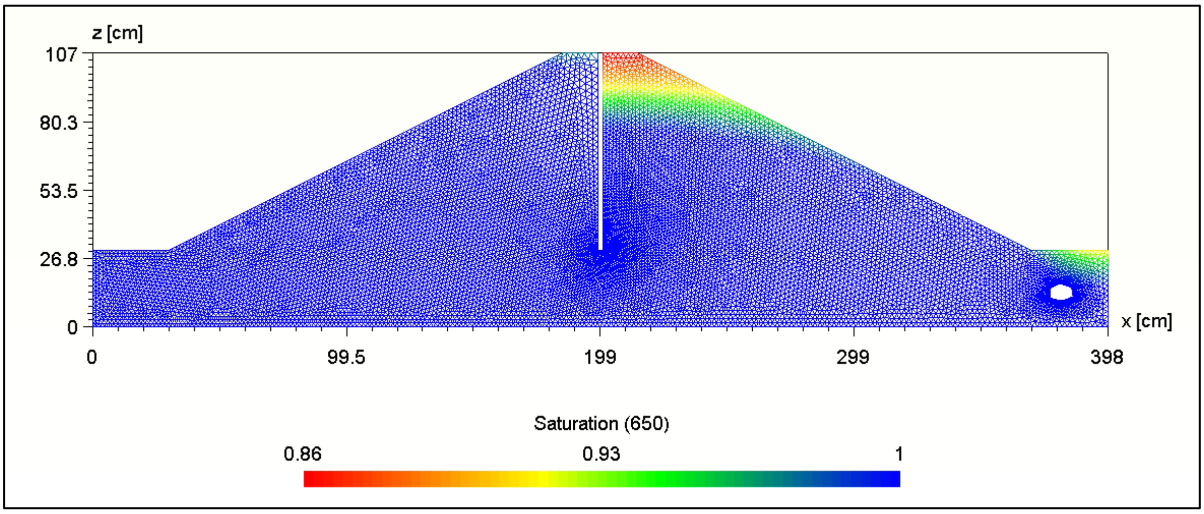

Fig. 5 - Saturation distribution in the levee at time = 650 min; at that time the flow regime can be regarded as steady-state

5 Conclusions and outlook

The ability to simulate transient flooding levels and their impact on the water content within dikes could be shown in principle. A more detailed analysis with regard to construction setup can be done to get information about the influence of used materials, the width, slope and height of the dike and so forth. E.g., the location and size of the drainage may have an impact to the water content distribution and should be considered to optimize the amount of drained water in case of a flooding.

To allow for the uncertainty of the material parameters of historical levees, the use of fuzzy set theory [6] is a suitable tool for regarding possible physical ranges of these parameters and their effects on the water content distribution within dikes and earth dams. But especially in case of transient problems, the demands for numerical analyses increase dramatically since the evaluation of the objective function (water content at a specific point within an earth dam) has to be executed at every single time step. Further improvements for the prognosis of the levee stability can be achieved through the combined consideration of the water content distribution and geotechnical calculations for land slide on the downstream face, crack formation and slope failure.

6 References

[1] Luckner, L., van Genuchten, M. Th. and Nielsen, D. R. A Consistent Set of Parametric Models for the Two-Phase Flow of Immiscible Fluids in the Subsurface. *Water Resour. Res.* 1989, 25(10), pp. 2187-2193.

[2] van Genuchten, M. Th. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Soc. Am. Journal.* 1980, 44, pp. 647-652.

[3] Kemmesies, Oliver. *Prozessmodellierung und Parameteridentifikation von Mehrphasenströmungsprozessen in porösen Medien.* Dresden : Dresdner Grundwasserforschungszentrum e.V., 1995.

[4] Mendoza, C. A., Therrien, R. and Sudicky, E. A. *ORTHOFEM User's Guide.* University of Waterloo, Ontario, Canada : Waterloo Centre for Groundwater Research, 1991.

[5] Aigner, Detlef. *Auswertung von Untersuchungen über den Einsatz einer Gummispundwand sowie einer Sickerleitung an einem durchströmten Modelldeich.* Institut für Wasserbau und Technische Hydromechanik. Dresden : Technische Universität Dresden, 2004. Gutachten.

[6] Schulz, Karsten and Huwe, Bernd. Uncertainty and sensitivity analysis of water transport modelling in a layered soil profile using fuzzy set theory. *Journal of Hydroinformatics.* 1999, Vol. 2, 01, pp. 127-138.

[7] Šimunek, J., Vogel, T. and van Genuchten, M. Th. *The SWMS_2D Code for Simulating Water Flow and Solute Transport in Two-Dimensional Variably Saturated Media.* Agricultural Research Service, U.S. Salinity Laboratory. Riverside, California : U.S. Department of Agriculture, 1994. p. 216, Research Report. Version 1.21.

[8] Haselsteiner, Ronald, Conrad, Marco and Strobl, Theodor. *Kriterien zur Ertüchtigung von Hochwasserschutzdeichen.* 5. Darmstadt-Berliner Baurechts-Kolloquium. Darmstadt : s.n., 2002. Kolloquium.

[9] Euler, Barbara, Kemmesies, Oliver and Gräber, Peter-Wolfgang. *2D-Modeling of flow processes in the unsaturated zone of wetlands.* Jaipur, India : International Groundwater Conference, 2008. Proceedings.

[10] OpenMP Application Program Interface. http://www.openmp.org/wp/openmp-specifications/