Simulation of Water Balance in Dump Slopes of Open-Cast Mining Pits for Geo Mechanical Stability Prognosis

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Abstract

Simulation of the water balance in open-cast mining areas is an important tool for assessing the risk of landslides taking place at the peripheral slopes of the pit. Since geomechanical instabilities in a soil can already occur at a water saturation values below 100%, a coupled simulation of unsaturated and saturated water flow has to be used for prognosis. This work introduces the individual tools used for the coupling, PCSiWaPro® and PCGEOFIM®, presents coupling strategies, and shows examples of unsaturated water flow simulations in slope bodies.

Keywords: dump slopes, stability, simulation, saturation

Introduction

Simulation of water flow in the unsaturated and saturated soil zone is a basis for the planning of environmentally sound and energy-efficient lignite mining, with lignite being one of the most important energy sources in Germany. The planning engineer shall be enabled to develop and to monitor sustainable water management with exemplary applications lying in the field of groundwater management in open-cast mining or in reclamation of post-mining landscapes. By using optimized simulations significant water resources can be protected (e.g. environmental protection to sustain natural wetlands) and the amount groundwater pumping can be lowered, thus saving energy.

With its various lignite deposits, open-cast mining became a very important economical factor in Eastern Germany. In most cases, the pits grew historically, and their dump slopes consist of an inhomogeneous and often unknown construction. Therefore, they do not fulfil the stability requirements of modern slope constructions. Especially in extreme precipitation periods, the hazard of collapse of the slope because of wetting increases. In the past this has already lead to extensive landslides, with damages to persons as well as property.

To estimate the stability of a slope, 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 slope 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 slopes may appear even if this zone is not fully saturated [Aigner, 2004].

Simulation tools PCSiWaPro® and PCGEOFIM®

As a basis for the upcoming coupled simulations, the software tools PCSiWaPro® by TU Dresden and PCGEOFIM® by IBGW® Leipzig are used.

PCSiWaPro®

Flow processes in the unsaturated soil zone can be described by the RICHARDS equation (1)

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

with volumetric water content θ, spatial coordinates x_i (x, z), capillary pressure head h, time t, K_{ij}^A and K_{iz}^A as components of a dimensionless tensor of anisotropy K, unsaturated hydraulic conductivity K depending on the pressure head, and a source/sink term S. The pressure head h is a dependent variable, and since both the hydraulic conductivity as well as the second dependent variable θ depends on h, the RICHARDS equation is a highly non-linear partial differential equation which needs to be solved iteratively.

The Institute of Waste Management and Contaminated Site Treatment of TU Dresden together with the "Ingenieurgesellschaft fuer Wasser und Boden mbH" developed the simulation software SiWaPro DSS. The latest version of this software, PCSiWaPro® (Graeber et al., 2006), implements the numerical solution of the RICHARDS equation in two spatial dimensions using a finite element approach. A graphical user interface (GUI) was developed to help the user create and manage models, create model geometries and to input soil parameters and initial and boundary conditions.

PCGEOFIM®

PCGEOFIM® (Mueller et al., 2003) is 3D simulation software for modelling fully saturated groundwater flow. It solves the groundwater flow equation (2) numerically by finite volume discretization.

$$S_0\frac{\partial h}{\partial t} + \frac{\partial}{\partial x_i}\left(k_f\frac{\partial h}{\partial x_i}\right) = V_v \qquad (2)$$

In equation (2) the following terms are included: storage coefficient S_0, pressure head h, time t, hydraulic conductivity k_f and volumetric flow rate V_v.

The software consists of two independent parts: the graphical user interface PCGEOFIM which is used to enter and manage all the data describing a particular model, and the simulation code Geofim which works as a command line tool and which is responsible for the numerical calculations. In comparison to other groundwater modelling software tools PCGEOFIM®'s unique feature is a set of boundary conditions especially designed for mining purposes, such as special kinds of wells and special consideration of surface water bodies.

There are two advantages of using a coupling of the two above-mentioned software programs in favour of a single tool, which solves the Richards equation for the whole flow area. The solution of the groundwater flow equation is computationally much cheaper than solving the Richards equation, due to the simpler structure of the linear system of equations resulting from discretization. The application of finite volume discretization compared to finite elements enforces this. Furthermore, PCGEOFIM® offers the user a unique set of methods and boundary conditions which are adapted to the specific technological conditions in open-cast mining. In order to utilize these features for slope stability prognosis taking into account unsaturated hydrological conditions, a coupling between this software and an unsaturated soil zone simulation tool had to be established.

Water saturation and slope stability

Slope stability problems are among the most commonly encountered problems in geotechnical and hydraulic engineering. Due to the practical importance of the subject, assessing the stability of a natural or man-made slope has received great attention across the geotechnical and hydraulic community for many decades. Since now there are lots of scientists who have done various researches in this field and some applicable numerical methods to analyze the slope stability have been developed. The typical methods are infinite slope equation, Ordinary Method of Slices, Bishop's Simplified Method, Janbu's Simplified Method, Spencer's method and Morgenstern-Price method.

Due to the close relationship between the water content and slope stability in the infinite slope equation, it is the most applicable equation to be used together with water flow simulation in unsaturated slope bodies. The infinite slope model is the oldest and simplest slope stability method that assumes identical conditions occur on any vertical section of the slope; however, this analytical model is not capable of modelling any kind of downslope variability. The infinite slope equation is usually implemented with the assumption of homogeneous or averaged soil properties in which geomechanical failures always occur at the base 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) (D.V. Griffiths, et al., 2011). The infinite slope equation for the factor of safety (FS) of a homogeneous soil, which is defined as the ratio of shear strength to shear stress for a one-dimensional infinite slope under both saturated and unsaturated conditions, is given as equation (3) (Duncan and Wright, 2005; Anne Witt and Rick Wooten),

$$\mathrm{FS} = \frac{C_r + C_s + \cos^2\theta[\rho_s g(D-D_w) + (\rho_s g - \rho_w g)D_w] \tan \varnothing}{D\rho_s g \sin\theta \cos\theta} \qquad (3)$$

with root cohesion C_r, soil cohesion C_s, slope angle θ, soil density ρ_s, water density ρ_w, soil depth D, water depth D_w, gravitational acceleration g and soil friction angle Φ.

As can be clearly seen in equation (3), the only necessary information about the water content in the slope body is water depth. More information can however be available as a result of field measurements or unsaturated soil zone simulation, like pore water pressure and residual volumetric water content. Then the infinite slope equation can be expressed as two parts (4) and (5) as shown below.

$$\sigma_S = - \frac{\theta - \theta_r}{\theta_s - \theta_r} (u_a - u_w) = - S_e (u_a - u_w) \tag{4}$$

$$\mathrm{FS}(z) = \frac{\tan \emptyset'}{\tan \beta} + \frac{2c'}{\gamma \, z \sin 2\beta} - \frac{\sigma_S}{\gamma z} (\tan \beta + \cot \beta) \tan \emptyset' \tag{5}$$

where σ is the total stress commonly provided by the self weight of the soil, σ_S is defined as the suction stress characteristic curve of the soil with a practical functional form (Lu and Likos, 2006); u_w is the pore water pressure, u_a is the pore air pressure, θ is the volumetric water content, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, and S_e is the degree of saturation. Transient data collected for both water content θ and soil suction (u_a – u_w) is used to calculate suction stress using equation (4). Then the factor of safety as a function of vertical depth z below the ground surface is given by equation (5), where Φ' is the angle of internal friction, c' is the cohesion coefficient, β is the slope angle, and γ is the soil unit weight depending on the water content (Lu and Godt, 2008). Infinite slope stability analysis is especially appropriate for those slopes in which the failure depth is relatively small compared to the landslide length (Lu and Godt, 2008).

When the factor of safety (FS) is reduced to less than unity, land-sliding is predicted. This can be explained by the fact that in areas with partial water saturation the reduced pore water pressure leads to a reduction of the weight and the friction coefficient of the soil grains, resulting in a reduced cohesion of the soil matrix.

Dam simulation with PCSiWaPro®

As an example of the simulation of the water balance in the unsaturated part of a slope with PCSiWaPro®, the following example briefly describes the simulation of an earth dam for a reservoir of mining water.

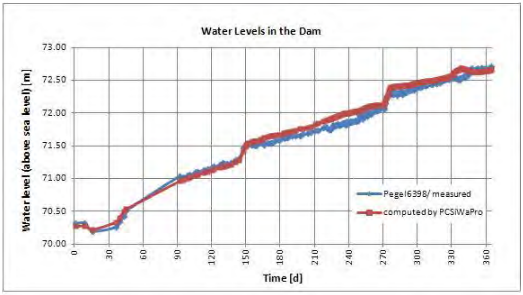
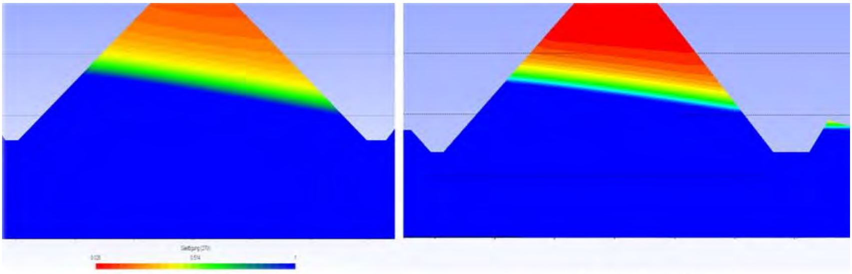


Figure 1 *Comparison between the computed and measured water levels in the dam*

For this simulation it was assumed that no precipitation water flows into the dam because the dam is covered with an impermeable layer of bricks, gravels and geotextiles.



α=2,5 m^{-1} , n=2

α=5 m^{-1} , n=2

Figure 2 *Impact of material parameters (left side shows a finer material than right side) on the water content in dam embankment*

The soil-hydraulic properties as well as the VAN-GENUCHTEN parameters are necessary for the model setup and were estimated using different data sources (Kemmesies, 1995; DIN 4220), since no measurements of the parameters were available. For this reason several scenario analyses have been carried out, in order to estimate the sensitivity of these parameters. PCSiWaPro® offers additional possibilities to estimate the parameters using measured data, such as pedotransfer functions (Vereecken, et al., 1989) and an inverse parameter identification algorithm. Figure 2 shows the sensitivity of the hydraulic material parameter α. Although the water level in the dam embankment hardly changed, a significant difference from the partially saturated zone above the seepage line could be observed. This zone is expanded by the increased capillarity of the more cohesive materials (greater capillary rise of water), and this can have a negative influence on the air-side stability of the dam.

Measured data, the water levels in an observatin well in the dam embankment, were compared for the program validation with simulated values. As can be seen in Figure 1, the agreement of the simulated and the measured values was very good.

Coupling PCSiWaPro® and PCGEOFIM®

The coupling of the two individual simulation tools is part of the ongoing research project EGSIM that is currently being carried out by the Institute of Waste Management and Contaminated Site Treatment and the IBGW® Leipzig. It is funded by the German Ministry of Education and Research. It is being carried out in order to enhance the currently available features of PCSiWaPro® to simulate the unsaturated soil water balance in pit slopes by taking into account groundwater table information from PCGEOFIM®, as well as to make unsaturated soil zone simulation available for the pure groundwater model PCGEOFIM®.

Since PCSiWaPro® can only simulate processes in two spatial dimensions; the first approach of the coupling of the two models will be restricted to planar cross-sections. PCSiWaPro® will simulate processes in the unsaturated soil zone and PCGEOFIM® in the groundwater zone. The common interface between the two models is the groundwater table. Since its depth can vary during the runtime of the simulation, both the PCSiWaPro® as well as the PCGEOFIM® model have to cover the whole area in which the groundwater table can possibly be during the simulation.

The coupling between the two models will be online, meaning that for each time step of a predefined exchange time pattern the models will exchange the following data:

- PCSiWaPro® calculates groundwater recharge at the current groundwater table in its model, and transfers it to PCGEOFIM®.
- PCGEOFIM® calculates the vertical position of the groundwater table, and transfers it to PCSiWaPro®.
- PCGEOFIM® transfers to PCSiWaPro® the horizontal discretization steps of the PCGEOFIM® volumes, which include the current groundwater table.

Groundwater recharge in PCGEOFIM® is applied as an upper boundary condition to the groundwater flow model. The depth of the groundwater level, however, cannot be applied purely as a lower boundary condition in PCSiWaPro®, since the groundwater table is generally situated at a depth somewhere within the PCSiWaPro® model. The implementation of the groundwater table into the PCSiWaPro® model is therefore carried out by adjusting the nodal values of the pressure head in the area that is covered by groundwater (pressure head of zero at the groundwater table, below that table linear increase with depth). This approach, however, interferes with the way the water balance is calculated in a PCSiWaPro® model. To level out the water balance equation, an artificial term has to be introduced to account for the manually added or removed amount of water. This term is determined by calculating the complete amount of water before and after the adjustment of the pressure heads. The difference between these two amounts is then interpreted as an artificial influx to or outfluxes from the model.

Exchange parameters (a) and (b) have to be calculated separately for every single PCGEOFIM® volume. This calls both for an individual groundwater recharge calculation for each volume, as well as for a volume-dependent (and therefore x-coordinate-dependent) adjustment of the pressure head values inside the PCSiWaPro® model. Depending on the current depth of the groundwater table the mapping of PCSiWaPro® nodes to PCGEOFIM® volumes, both of which represent the current groundwater table in the respective model, can change. This makes it necessary to exchange the corresponding horizontal discretizations of the models at the current groundwater table for each data exchange time step.

Software communication between the two models will be carried out by text files or by shared memory variables. While the first option is often used for coupling individual simulation models (e.g. in Sames et al., 2004), tests with exchanging data by shared memory variables proved to be a faster and more stable approach in comparison to text or binary files.

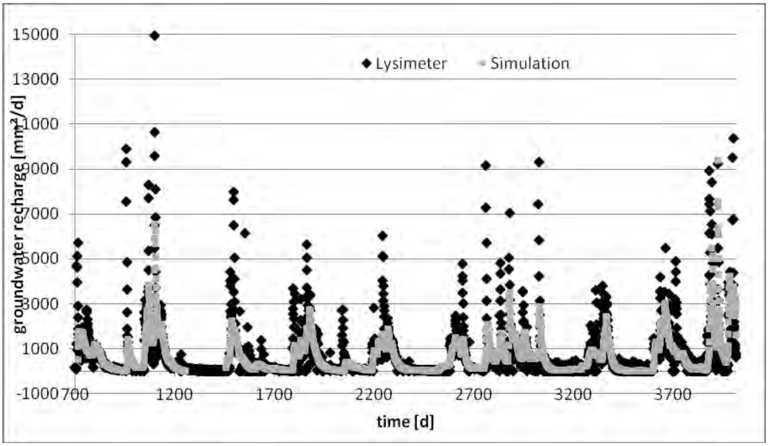


***Figure 3** Validation of the new PCSiWaPro® routine for groundwater recharge calculation against lysimeter data. The thick dots are simulated PCSiWaPro® recharge fluxes, the small dots are measured lysimeter outfluxes.*

To calculate groundwater recharge at any point inside of a PCSiWaPro® model, a new routine had to be implemented. The following workflow was applied:

Detection of the nodes which form the groundwater table at the current time step. The groundwater table in a PCSiWaPro® model is defined as the collection of nodes, whose pressure head is equal to or greater than zero, and who have at least one neighboring node whose pressure head is below zero. Since due to saturation and ponding effects an identical scenario can also occur in other parts of the unsaturated soil zone model, the depth of the groundwater table which is received from PCGEOFIM® is used as a first z-coordinate estimate to find the corresponding nodes.

Calculation of nodal fluxes for the nodes of the current groundwater table. This is carried out by using the pressure heads at the node itself and at the surrounding nodes, combined with the geometry data of the finite elements.

Calculation of fluxes over the element edges that form the groundwater table. By multiplying the nodal fluxes with the length of the element edges that form the groundwater table, the values of groundwater recharge for the whole length of the groundwater table are calculated.

Summing of edge fluxes according to the PCGEOFIM® volume discretization. Since the horizontal length of one PCGEOFIM® volume usually comprises more than one groundwater table element edge in the PCSiWaPro® model, the calculated edge fluxes have to be grouped and added to determine the final groundwater recharge value for each PCGEOFIM® volume.

This new routine was validated against measured lysimeter data of a 3 m column of undisturbed eroded cambisol. The PCSiWaPro® model consisted of a 3.5 m column, with a groundwater table lying in 3 m depth. The comparison between the simulated and measured values (Figure 3) showed that the routine can predict the time variation of the outflux very well. However, the exact flow values of the peaks could not be reached. This is due to the fact, that the VAN-GENUCHTEN soil parameters, which drive water flow in the unsaturated soil zone, could only be determined by pedotransfer functions, which introduces inaccurateness into the model results.

Conclusions

A concept has been developed to improve the currently available capabilities of simulating the water balance in open-cast mining pit slopes. For this purpose an unsaturated soil zone simulation model with a groundwater simulation model will be used for a coupled simulation. The coupling will be based on two-dimensional cross-sections, and data will be exchanged during the simulation runtime. First implementations have been carried out by calculating groundwater recharge for a groundwater table lying in an arbitrary depth inside the unsaturated soil zone model. This new routine has been successfully tested against measured lysimeter data.

Future tasks lie in the using the simulated values of water saturation in actual calculations of the geomechanical stability of the slopes, using the equations and models presented in this paper.

References

Aigner, Detlef. 2004. Auswertung von Untersuchungen über den Einsatz einer Gummispundwand sowie einer Sickerleitung anneinem durchströmten Modelldeich. Institut für Wasserbau und Technische Hydromechanik. Dresden : Technische Universität Dresden, 2004. Gutachten.

Anne Witt and Rick Wooten; LiDAR and landslides: Utilizing GIS in the NC Landslide Hazard Mapping Program; North Carolina Geological Survey

DIN 4220: Deutsches Institut für Normung e. V. Bodenkundliche Standortbeurteilung - Kennzeichnung, Klassifizierung und Ableitung von Bodenkennwerten.

Duncan, J. M., and S. G. Wright (2005), Soil Strength and Slope Stability, 297 pp., John Wiley, Hoboken, N. J.

D.V. Griffiths, Jinsong Huang, Gordon A. Fenton, 2011; Probabilistic infinite slope analysis; Computers and Geotechnics 38 (2011) 577–584

Graeber, P.-W. et al., SiWaPro DSS - Beratungssystem zur Simulation von Prozessen der unterirdischen Zonen - In: Müller, Mike - Simulation in Umwelt- und Geowissenschaften, Shaker Verlag 2006.

Kemmesies, Oliver. 1995. Prozessmodellierung und Parameteridentifikation von Mehrphasenströmungsprozessen in porösen Medien. Dresden : Dresdner Grundwasserforschungszentrum e.V., 1995. ISSN 1430-0176.

Lu, N., and J. W. Godt (2008), Infinite-slope stability under steady unsaturated conditions, Water Resour. Res., 44, W11404, doi:10.1029/ 2008WR006976.

Lu, N., and W. J. Likos (2006), Suction stress characteristic curve for unsaturated soil, J. Geotech. Geoenviron. Eng., 123, 131–142.

Mueller, M. et al., PCGEOFIM - A finite volume model for more? - In: Proceedings of the Conference MODFLOW and More 2003: Understanding through Modeling. Golden, Co, USA. September 16 - 19, 2003.

Sames, D. et al., KliWEP - Abschätzung der Auswirkung der für Sachsen progonostizierten Klimaveränderungen auf den Wasser- und Stoffhaushalt im Einzugsgebiet der Parthe. Final research report, 2004.

Vereecken, H., et al. 1989. Estimating the soil moisture retention characteristic from texture, bulk density and carbon content. Soil Science. 1989, Vol. 148, No. 6, pp. 389-403.