Aspects of 3D Seepage Analysis of Dams and Levees – Case Studies

B. Ersoy & R. Haselsteiner
Bjoernsen Consulting Engineers, Koblenz, Rhineland-Palatinate, Germany

ABSTRACT:

The development and evaluation of pressure heads, hydraulic gradients and flow discharge rates through an embankment dam or levee body and the corresponding foundation plays a significant role during the design stage and later operation since an uncontrolled increase of seepage flow may cause failure mechanism such as piping, internal erosion, and general slope instability.

In order to evaluate the stability of an embankment dam, 2D seepage analyses are usually performed as a common method. For long, uniform embankment structures founded on uniform subsoils and bearing the same load conditions this is an appropriate approach. However, as soon as local in-homogeneities such as horizontal damages in sealing systems, longitudinal cracks, roots, animal pipes, etc. occur, 2D analyses cannot consider 3D seepage flow conditions and, in many cases, the 2D approach overrates the seepage conditions. Additionally, the calibration by the results of real measurements leads to an underestimation of the geotechnical parameters.

In the paper, academic and real case studies will be presented in order to visualize the effect of in-homogeneities in dams and levees on seepage flow. One of the presented case studies is a reservoir dam at the Danube River in Germany which shows weaknesses concerning its surface sealing.

1 INTRODUCTION

All earth and rock-fill dams are subject to seepage occurring through the sealings, embankment fills, foundations, and abutments. Seepage control is necessary to prevent excessive uplift pressures, instability of the downstream slope, piping through the embankment and/or foundation, and erosion of material by migration into open joints in the foundation and abutments.

In order to evaluate the stability of an embankment dam, 2D seepage analyses are usually performed as a common method. 2D seepage models, while providing valuable information, cannot adequately model realistic conditions in case of in-homogeneities, horizontal damages, longitudinal cracks, backward erosion and piping occur due to the corresponding three dimensional effects.

In many cases, 2D seepage analysis overrates the line of seepage and the seepage flow also depending on the assumptions of leakages, malfunctions, etc. of sealings or drains as stipulated in many design codes such as the DIN 19712 for levees in Germany. The necessity of te consideration of three dimensional effects and 3D seepage analysis is obvious as the case studies show as more realistic results by 3D modeling lead also to a better understanding of the factual applied safety level of the engineering structures and their behaviour in case of failure.

2 FUNDAMENTALS

2.1 *Seepage flow and equations*

The analysis of seepage started with the development of Darcy's law in 1856, and the realization that the Laplace equation governing heat and current flow was also applicable to the steady-state flow of an incompressible fluid.

Darcy's law can be used to describe water flow through soils in both saturated and unsaturated conditions (Richards, 1931) which can be stated as follows:

$$q = k \times i \tag{1}$$

where q = discharge per unit area, k = co-efficient of permeability, i = total head gradient.

Usually, the linear correlation between head and flow rate is limited to medium permeable soils such as sands. For soils with a very low or high permeability the linear correlation is not valid anymode, but pre- and post-laminar conditions are usually not considered in practice. Those effects are mainly covered by the selection of a representative permeability.

Seepage flow may be steady or unsteady (transient), confined or unconfined with a phreatic surface. Seepage condition underneath or through an earth dam, is initially unsteady, however, steady state seepage condition occur after elapse of enough time. The formulation for the unsteady state condition in three-dimensional system is given as follows:

$$\frac{\partial}{\partial x}\left(k_{wx}\frac{\partial h_w}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{wy}\frac{\partial h_w}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{wz}\frac{\delta h_w}{\delta z}\right)=\frac{\partial \theta}{\partial t} \tag{2}$$

where k_{wx}, k_{wy}, k_{wz} = hydraulic coefficients of permeability in x, y and z directions, h_w = total head, θ = volumetric water content, t = time.

Equation 2 states that rate of flow into a soil element plus the external applied flux is equal to the rate of change in the volumetric water content with time. For a steady state seepage condition, the right hand side of the Equation 2 is set to zero and, in general, modeling becomes much easier especially concerning the initial conditions as well as computing time.

The flow of fluids in soil obeys the same fundamental equations for streamline flow. The Laplace equation for both curvilinear and linear flow expresses the behaviour of flow through the soil pores. Laplace assumed that the soil is incompressible and homogeneous. The flow through the soil medium adopts Darcy’s law. If the permeability k value is constant and linear;

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\nabla\nabla h=0 \tag{3}$$

Equation 3 is a general shape of the Laplace equation in three dimensions for water flow within soils.

2.2 *Soil functions and parameters*

The mechanical behaviour of unsaturated soils is mostly influenced by the degree of saturation and, consequently, by the matrix suction. Matrix suction is a function of many soil properties such as the grain size and the geometry and distribution of the pores (see Figure 1). In addition, matrix suction depends on the pore fluid properties such as the interfacial forces, density, and the degree of saturation.

In order to assign reliable inputs to the numerical model, the main geo-hydraulic parameters are implemented that are presented, e.g., in Haselsteiner (2007) and the related literature sources. In Haselsteiner (2007) the geo-hydraulic parameters are compiled from 17 different literature sources. The compiled geo-hydraulic parameters are categorized in accordance with typical embankment dam materials and zones plus underground soils the curves for the matrix suction and relative permeability related to the degree of saturation are defined based on the equations that are presented in Figure 1.

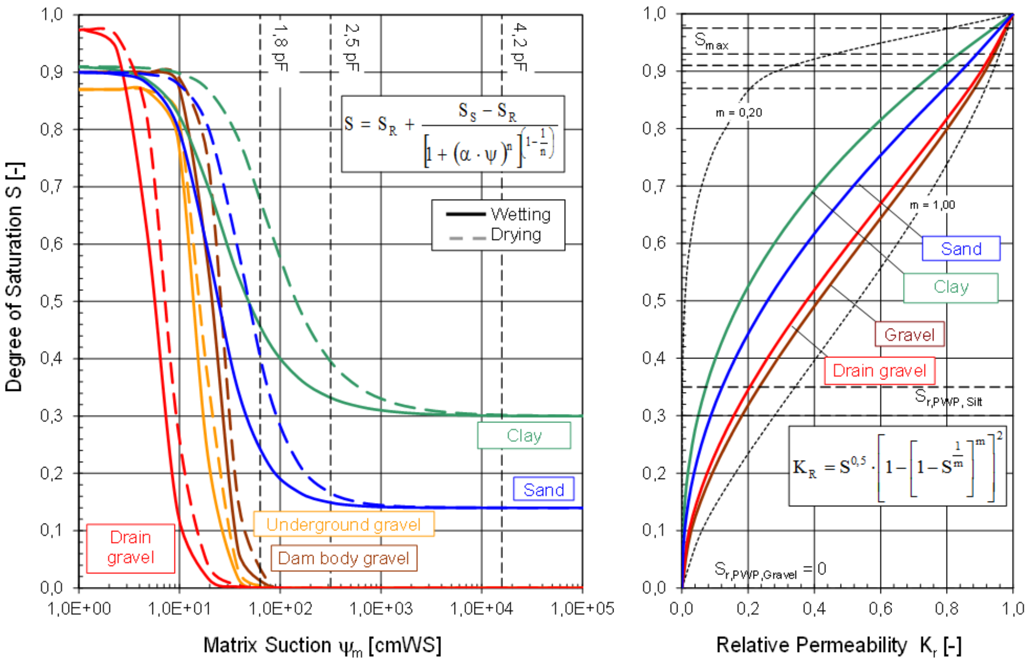

Figure 1. Relation between degree of saturation, the matrix suction and relative permeability for different typical embankment dam and foundation materials after the Van-Genuchten-model (taken from Haselsteiner, 2007)

2.3 *Steady state consideration*

In a seepage analysis, the “state” refers to the water pressures and water flow rates. Steady state analysis does not consider time to achieve the steady state condition.

Since steady-state analyses ignore the time domain, it gives a possibility to solve the problem easily and, usually, conservatively.

In a steady state analysis of embankment dam seepage usually two types of boundary conditions are selected:

- a constant pressure (or head)
- a constant flux rate/seepage exit

For convenience the flux rate can be specified as a total nodal flux or a unit flux applied to an element edge, but the end result applied to the equations is identical. It is either a known pressure at this point, or there is a continuous inflow or outflow of water.

3 MODELING

In order to analyze embankment dams and levees, mathematical models are needs to be developed. Commercial software packages are available such as FEFLOW or in SEEP/W. SEEP/W is a finite element software product that is part of the GEOSTUDIO software package. It is formulated on the basis that flow of water through saturated and unsaturated soils follows Darcy’s Law. The SEEP/W model is constructed to solve 2 and 3-dimensional flow situations with multiple soil layers and is used for the work described in this paper

To evaluate and compare the results of the 2D and 3D seepage analyses, observation points are defined. In order to assess the three dimension effects, the observation points are assigned in z-direction along different sections as presented in Figure 2.

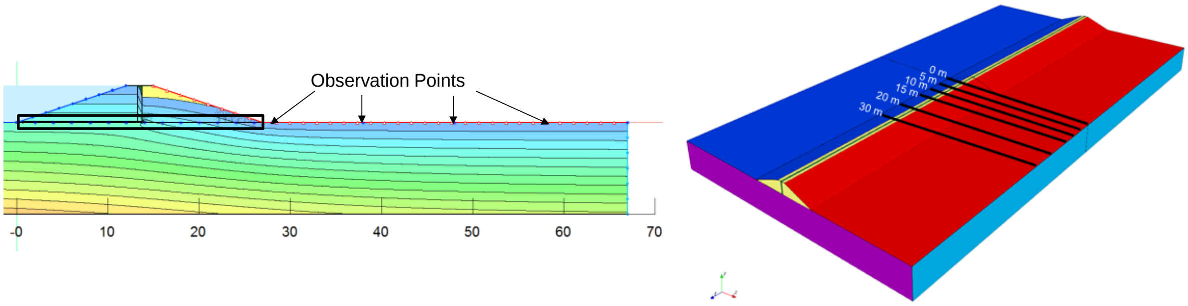

Figure 2. Exemplary sketches for the selection of observation lines in 2D and 3D numerical models

In order to determine the seepage flow though the embankment body, a Finite Element Method (FEM) requires the definition of boundary conditions as aforementioned. Following boundary conditions have to be defined:

- The “constant head” type of hydraulic boundary condition is selected at the upstream face of the numerical model by considering the maximum water level or the design flood water level.
- The “constant head” type of hydraulic boundary condition is selected at the downstream face of the numerical model by considering the water level at the downstream side or the groundwater level.
- The ”total flux type” of hydraulic boundary condition is applied for potential seepage exit areas along the downstream side of the numerical model where the pressure is set to “zero”.

More details regarding the model size and the meshing are given in the case study description below.

4 DESCRIPTIONS OF CASE STUDIES

4.1 *Academic case study*

2D and 3D seepage analyses were conducted by Haselsteiner (2007) and the results are compared accordingly in order to evaluate the three dimensional effects on the analyses. To develop a numerical model by using SEEP/W software, the representative cross section as presented in Haselsteiner (2007) is adopted. A typical dike cross section with a height of 4 meters is used. The model size (width) was defined in consideration of the dam height, as minimum 5 to 10 times the dam height to up- and downstream so that the boundary conditions are not influencing the seepage flow. This results in a model width of 107 meters. The modelled underground depth was selected as minimum two times the dam height that is approx. 10 m. The width of 3D numerical model is developed as 200 m in z-direction (Figure 4), showing 100 m to the left and 100 m to the right of the section where a leakage element is applied, here in form of a pipe/crack penetrating also the sealing of the dike.

The upstream and downstream slope of embankment is taken as V:H = 1.0 : 3.0. Maximum water level is 4 m above the upstream surface level (crest impoundment according to DIN 19712/2013). The zones are defined according to Haselsteiner (2007) consisting of the levee body and the sealing. As a last step, the subsoil conditions are defined in the numerical model. A 10 m deep clay layer is defined as underground material. The final view of the numerical model that used in seepage analysis is given in Figure 3. The underground/foundation layer shows a very low permeability so that the seepage flow through the dike body and the underground are practically independent (see also Haselsteiner, 2007, 2007a, 2008).

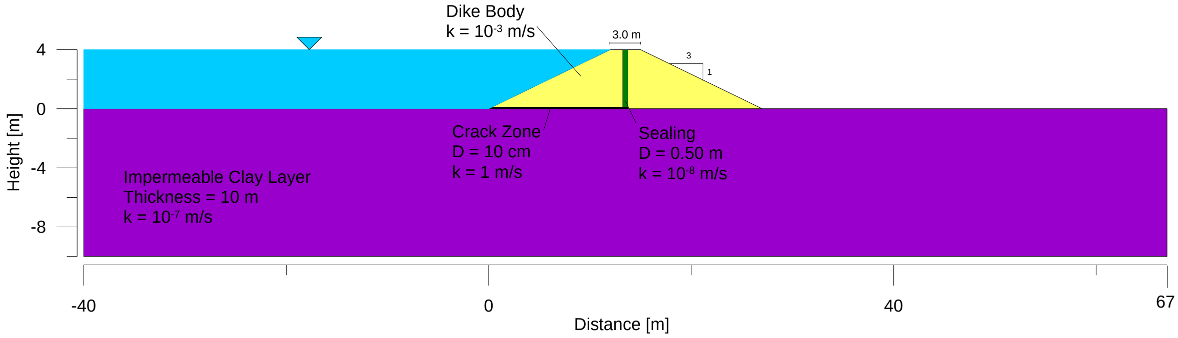

Figure 3. 2D cross section of the academic dike case study (Haselsteiner, 2007)

In order to see the effect of the crack dimension, the different options are developed in 2D numerical model and adopted to 3D analysis as well. In the first option the crack zone is defined through the upstream side of the dam body until the end of sealing element as considered also in Haselsteiner (2007). Thus, a complete long crack in connection to the upstream water level was assumed. In Option 2, the size of the crack zone is reduced to only the sealing zone.(see Figure 4).

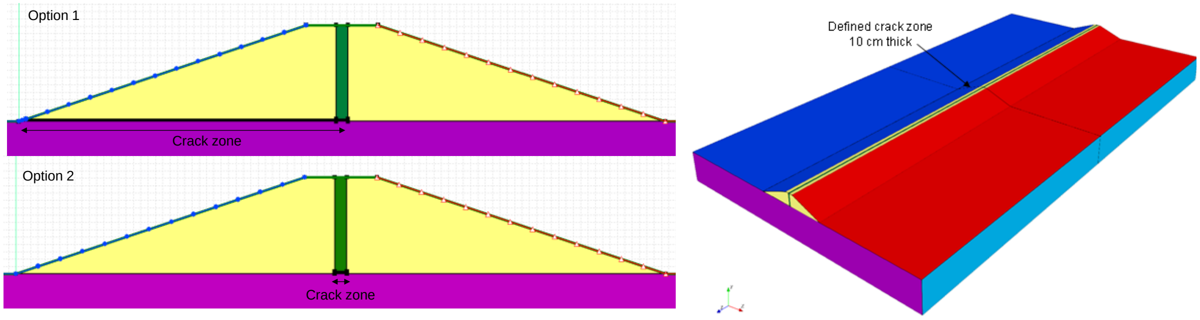

Figure 4. 2D and 3D numerical model of the academic dike system as prepared in SEEP/W

The next step in developing a numerical model in SEEP/W is to assign materials to the regions as defined in the numerical model above. The geo-hydraulic parameters shown in Figure 1 are the key parameters. The material model (saturated only, saturated/unsaturated and interface) is selected. ‘Saturated/unsaturated’ option was selected for the 2D and 3D seepage analyses for all materials. The following volumetric water content and hydraulic conductivity functions are used for the assigned materials that are obtained in accordance with the sub-chapter 2.2 (Figure 5 and Figure 6, see also Figure 1).

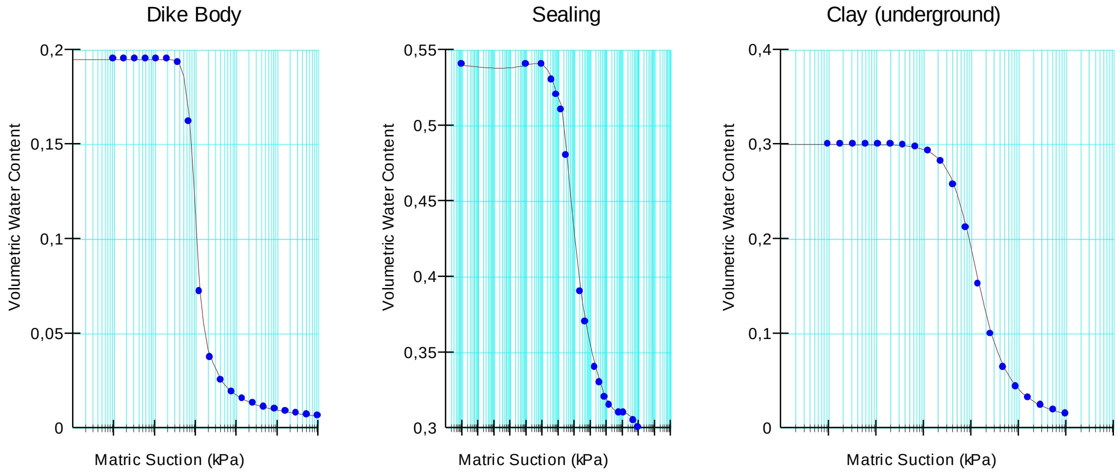

Figure 5. Volumetric water content functions for the assigned materials

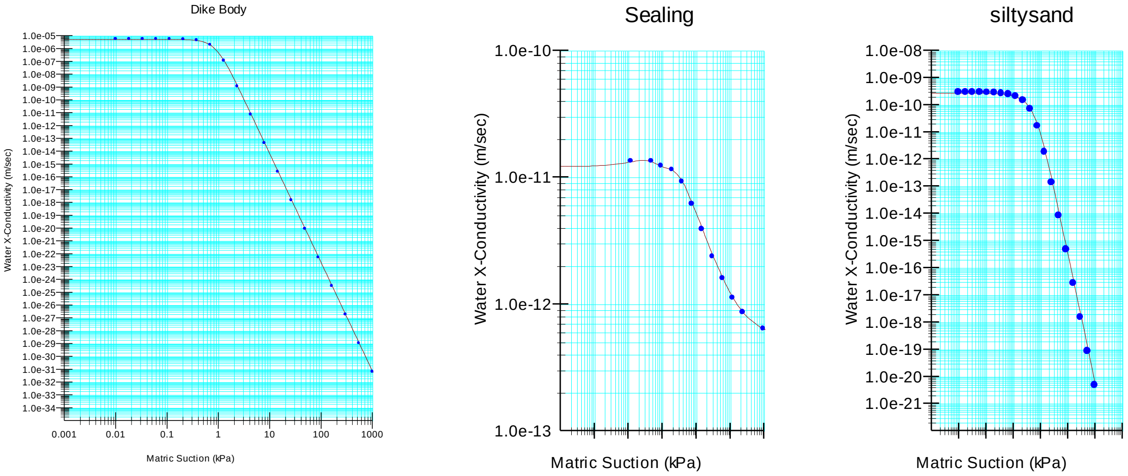

Figure 6. Hydraulic conductivity functions for the assigned materials

The FEM mesh was created by selecting a global element size for meshing of 0.2 m for 2D and 1 m for 3D numerical model in consideration of the required accuracy and the required computing time. For a better possibility of evaluation the zero point (x, y) = (0, 0) was set at the upstream dam toe as indicated in the Figure 7 below and for the 3D model adequately.

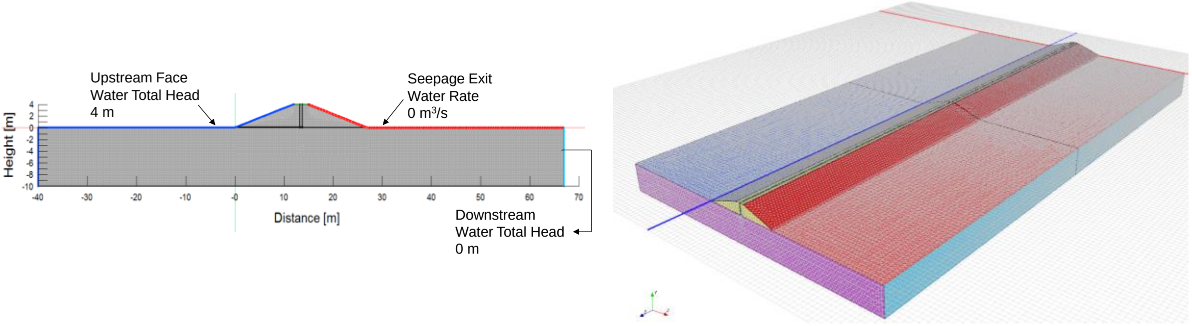

Figure 7. 2D and 3D numerical models of the academic dike with FEM mesh and boundary conditions

4.2 *Real case study – reservoir dam Bavaria*

As a second case study a reservoir dam that is located in Bavaria, Germany, was investigated. A typical embankment dam cross section with a height of 2 meters is considered in the numerical model. The model size (width) is defined as approx. 100 meters. The modelled underground depth was selected as minimum two times the dam height that is 10 m. The width of 3D numerical model is developed as 200 m in z-direction (Figure 10).

The upstream slope of embankment is taken as V:H = 1.0 : 1.6 and the downstream slope of embankment is taken as V:H = 1.0 : 2.2. Maximum water level is 1.5 m above the upstream surface level. A 2 m deep clay layer is defined as foundation material. The final model is given in Figure 8.

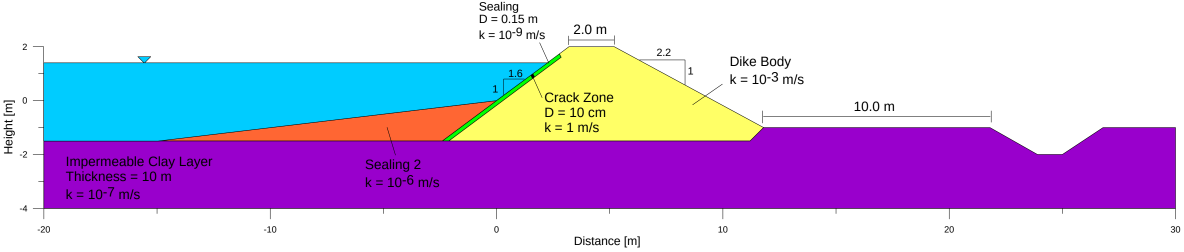

Figure 8. Typical 2D Cross Section of the reservoir dam case study

‘Saturated/unsaturated’ option was selected for the 2D and 3D seepage analyses. The volumetric water content and hydraulic conductivity functions for the dam body and clay layer are chosen corresponding to the first case study. The functions for the zones are presented in Figure 9.

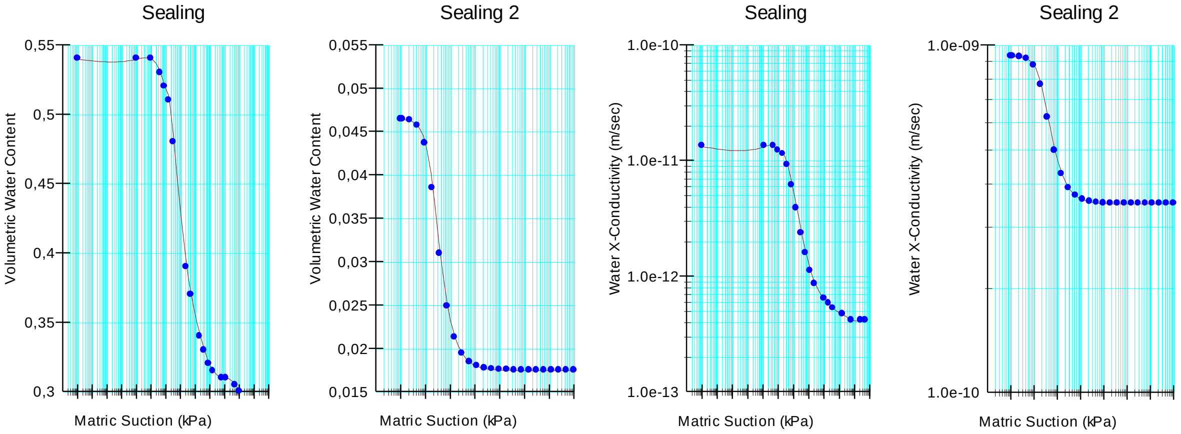

Figure 9. Volumetric water content and hydraulic conductivity functions for the assigned materials for the embankment dam case study

The FEM mesh was created by selecting a global element size for meshing of 0.2 m for 2D and 1 m for 3D numerical model. The zero point was set as shown in Figure 10 below.

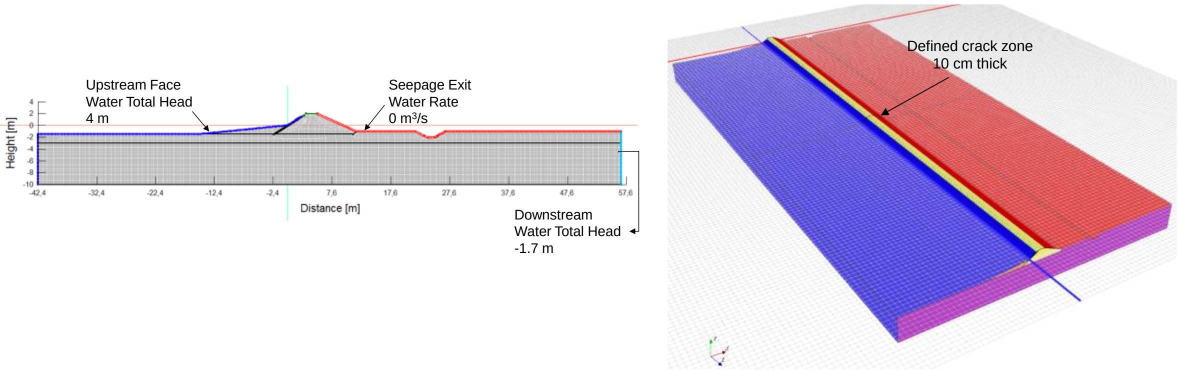

Figure 10. 2D and 3D Numerical models with FEM mesh and boundary conditions

5 RESULTS AND INTERPRETATION

5.1 *Results - academic case study dike with center sealing*

In accordance with the assignments that are explained in the chapters above, 2D and 3D seepage analyses are performed. The results are evaluated considering three aspects as follows:

For option 1, the crack zone is defined through the upstream side of the dam body penetrating also the sealing element as done also in Haselsteiner (2007) (see Figure 11 and Figure 12). The water pressure head results show that there is a significant difference between two and three dimensional analyses (see Figure 11). 2D results reflect higher water pressure head than 3D results that are considered as more realistic in case of a continuous seepage through the dam foundation since the seepage flow can flow in three directions which leads to a faster pore water release in the downstream body.

Besides the comparison between 2D and 3D analyses, the situation of water pressure head in the third dimension (z) away from the crack section is evaluated as well. As seen in Figure 11, the water pressure head results decreases when the distance between the crack zone and the observation points increase.

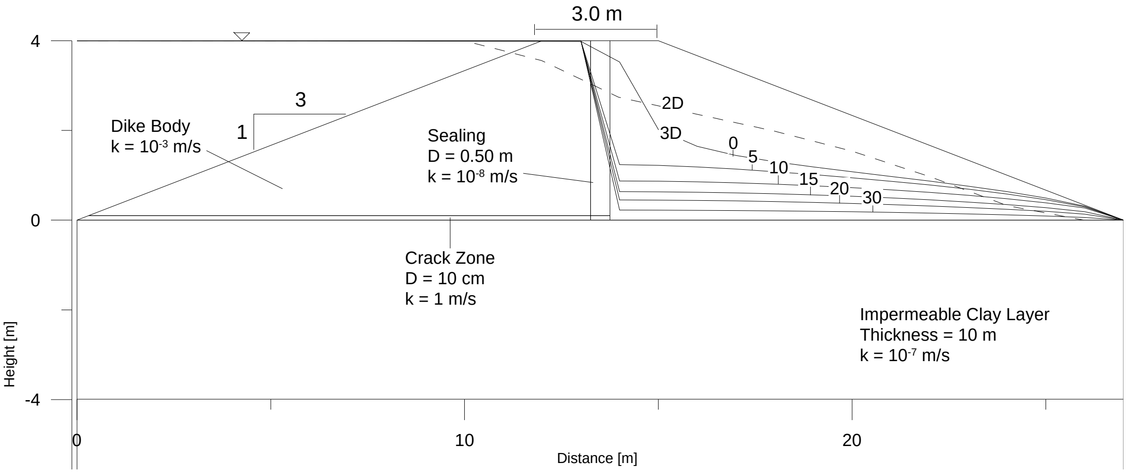

Figure 11. Pore water pressure distribution for the dike case study in sections with a distance of 0 to 30 m distance for the crack model option 1

The results that are obtained from SEEP/W are compared with the results of Haselsteiner (2007). As seen in the Figure 12 the water pressure head results for the 2D and 3D seepage analyses are in the same range although there are some differences which can be caused by the different seepage software and the different modeling approaches concerning meshing and solving equations. Haselsteiner (2007) used a FEFLOW model for the seepage analyses.

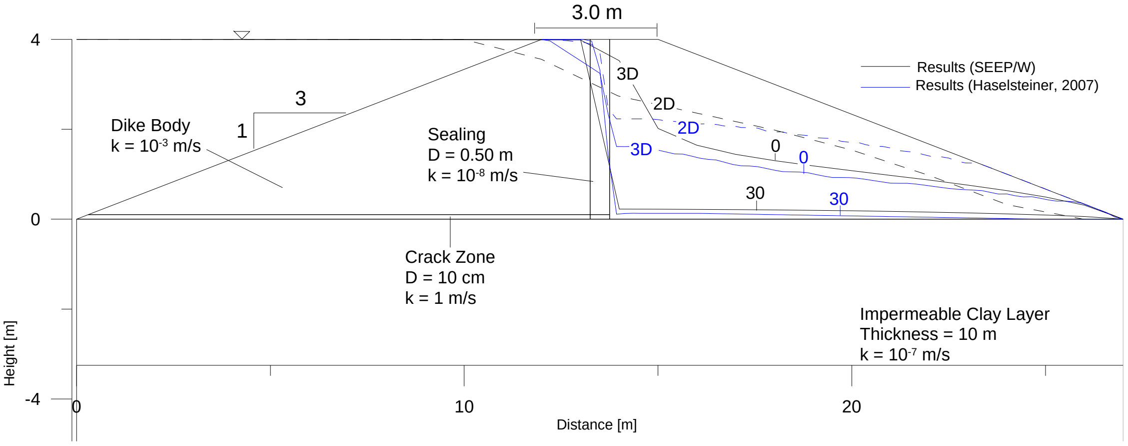

Figure 12. Comparison of the results of SEEP/W for the dike case study from (Haselsteiner, 2007)

In Option 2, where the crack/pipe was limited to the width of the sealing element, the size of the crack zone is reduced in order to evaluate the difference of the pore water pressure distributions of the 2D and 3D analysis (see Figure 13). The crack zone shall represent a damage at the bottom of the sealing.

As seen in Figure 13, there is not a significant effect on the 2D and 3D results in case of a 10 cm damage at the bottom of the sealing system within the leakage section (0 m). Similar to the crack modeling of option 1 also for option 2 pore water pressure decreases with increasing distance from the crack section.

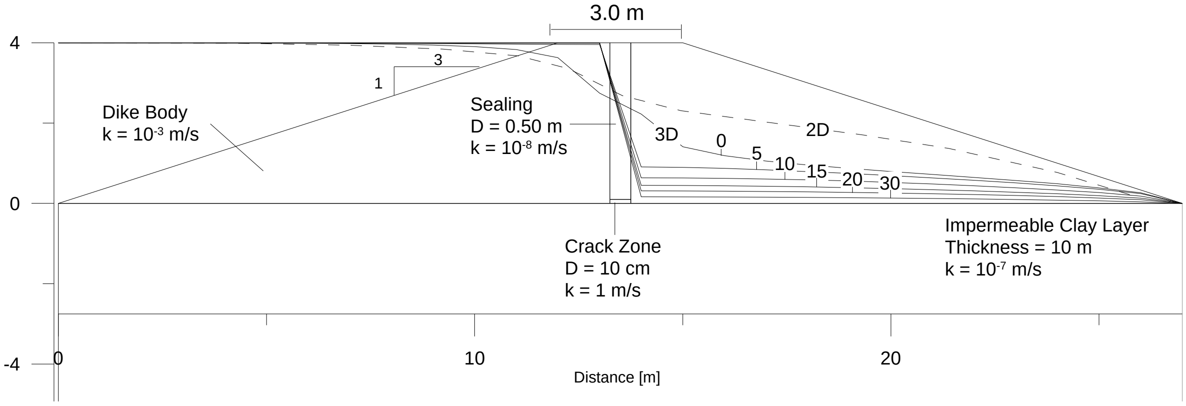

Figure 13. Resulting pore water pressures of crack modeling (option 2) for the dike case study

5.2 *Results - real case study – reservoir dam Bavaria*

The 2D and 3D seepage analyses are performed and the results are compared in order to evaluate the pore water pressure in the dam body in case of a crack occurrence in the upstream sealing system which consisting of a concrete slab on the surface.

The results of the 2D and 3D seepage analyses are presented in Figure 13. The water pressure head results corresponded with the academic case study in regard with the 2D and 3D comparison. 2D seepage analysis results show higher pore water pressures than the 3D seepage analyses results also in section 0 m. The pore water pressure in the dam body is resulting in accordance with the occurrence of the crack zone in the sealing system as expected. Besides, the water pressure head results in 3D analyses decrease smoothly considering the observation points that are classified according to the distance between 0 and 30 m. The smooth detention of the pore water pressures also are a result of the considerable detention in the crack section.

Since the crack is directly connected to the reservoir the crack modeling type (option 1 or 2) is not relevant because the full water pressure loads the crack.

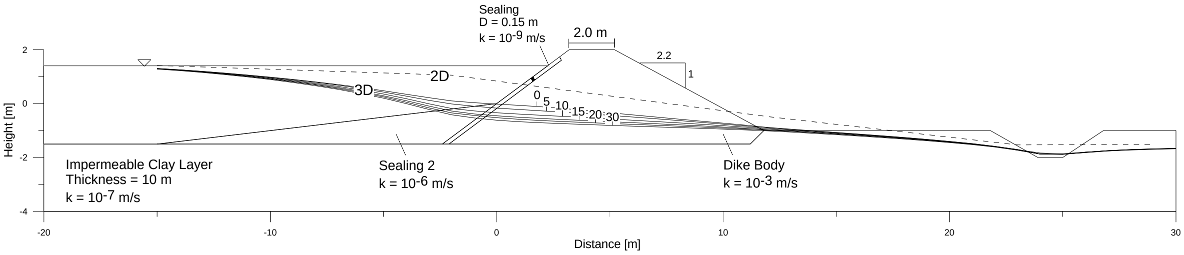

Figure 13. Resulting pore water pressures for the dam case study with a crack in the surface concrete sealing

5.3 *Interpretation*

The 2D and 3D seepage analyses and the assessment of the results of the academic and real case studies revealed following results and comments:

- 2D seepage analyses end up with more conservative results.. Therefore, 3D seepage analyses results in more accurate and realistic pore water pressure distributions since three dimensional detentions effects are considered downstream of the sealing.
- The open/damaged sealing or restricted functionality of the sealing system cases affects the seepage conditions in 2D and 3D analyses. The assumptions of crack modeling (here: option 1 or 2) are important and have to be defined in consideration of the specific dam conditions.
- The effect of the seepage is evaluated in the third direction (z) by the 3D seepage analysis. The water pressure head results are decreases when the distance between the crack zone and the observation points increase as expected.

- 2D analyses cannot consider the 3D seepage flow conditions and, in many cases (inhomogeneities such as horizontal damages in sealing systems, longitudinal cracks, roots, animal pipes, etc.), overrates the line of seepage and the seepage flow.

The efforts for 3D analyses are usually very high, since a 3D model need to be prepared. As soon as the 3D model can be easily derived from an existing 2D model by simple extraction as the 3D modeling tool (3D SEEP/W) enables also 3D analyses can be performed quickly. Major efforts and knowledge have to be concentrated on the crack modeling and the definition of the design situations or load cases so that also realistic 3D relevant elements are applied, such as pipes, cracks, leakages, roots, etc.

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