Influence of Increased Precipitation on the Transient Seepage Through Levees during Flood Events

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ABSTRACT: The transient seepage through levees during a flood event depends on several factors, such as the initial water content condition within the levee as a result of former flood and precipitation events which is frequently neglected. Results of experimental and numerical investigations are presented which show the importance of the initial water content distribution on the resulting transient seepage. Analytical methods for calculating the transient seepage through levees are introduced. The modified method after Brauns (1999) allows for the determination of the seepage through levees under consideration of partly saturated conditions. The initial conditions for the transient seepage can be chosen based on simple considerations related to the field capacity or the effective infiltration of water due to precipitation.

KEYWORDS: Transient seepage, Levees, Precipitation, Initial conditions, Analytical methods

1. INTRODUCTION

Levees along rivers are the main technical measure against flooding. These structures are mostly designed for a flood event with well-defined probability of occurrence. In the case of a flood, levees are hydraulically loaded leading to (1) overtopping when the water level exceeds the height of the levee, (2) seepage beneath the levee through the aquifer the levee is based on and (3) seepage through the levee. In the case of seepage through the levee, the structure is close to failure when the phreatic surface reaches the downstream side slope. The time required for the phreatic surface to reach the downstream side slope is critical in the sense that it should be always larger than the duration of the flood.

The transient seepage through levees during floods is influenced by different parameters and conditions, such as levee material and geometry, height and duration of the flood, and the levee structure inclusive any deficiencies caused by burrow animals or plants. One important, often overlooked factor is the initial condition of the levee material in terms of the water content distribution before the occurrence of the flood event. The initial water content of the levee material influences the transient seepage in two concurrent ways: On the one hand, for higher saturations less water infiltrating the pore space is required for the progress of the seepage front as only the air-filled pore space needs to be filled. On the other hand, for higher saturations matric suction is reduced which is an additional potential driver for the movement of the water front.

From mechanical point of view, if the levee is built of soils with dominant fine-grained fraction, an increase in water content leads to softening of the levee material accompanied by the loss in strength as suction and as a consequence apparent cohesion get lost. Under loading during flood, levees at high water content condition can fail due to mechanical disturbances, such as a mechanical shock caused by falling sand bags on the levee body or the vibration created by a helicopter flying in low heights over levees when they are extensively defended during flooding.

The initial water content distribution can be increased by former minor floods or by continuous, long-lasting rain events. It is well-understood that the occurrence and extend of both, floods and precipitation events, are subject to changes due to climate change. It depends on the climate region whether precipitation increases or decreases. But, the unanimous opinion of meteorologists and climate experts is that extremes are occurring more frequently. In this connection, the occurrence of the flood at a specific levee section might not be necessarily connected to the precipitation event from a statistical point of view. Especially for larger streams, floods can originate in more distant regions than the levee section under consideration.

The influence of the initial water content condition on the transient seepage through levees is still a less investigated topic. This contribution presents results of a study aiming at the quantification of the influence of the initial water content on the transient seepage through levees. Analytical solutions for determining the transient seepage are introduced and results of experimental investigations are presented. A numerical study based on 28 years of meteorological observations reveals the importance of the initial water content condition. A modified version of the method after Brauns (1999) is suggested for determining the water content dependent transient seepage though levees.

2. TRANSIENT SEEPAGE THROUGH LEVEES

2.1 Analytical solutions

In the case of a flood event, levees are hydraulically loaded for a limited period of time. During this time, water infiltrates into the levee body even during receding flood wave. The transient seepage of water through the body of a levee is dependent on many factors (Schneider, 1997):

- Geometry of the levee body (relatively considered water flows faster through smaller levees than through bigger ones),
- Hydraulic conductivity of the levee material,
- Structural composition of the levee body (density of levee material, layering) inclusive deficiencies originating from burrow animals and plants,
- Temporal evolution of the flood wave,
- Initial water content condition within the levee body at the arrival of the flood wave.

There are several analytical methods available for the determination of the transient seepage through levees, which take into account one or several of these factors. All of these methods have in common the assumption of a homogeneous levee founded on a waterproof base. A less known semi-empirical method was developed by Dvinov (1987) which is based on the analytical solution of Polubarinova-Kochina (1962) for the transient seepage through a rectangular earth body. Dvinov conducted seepage tests using Hele-Shaw cells with inclined upstream side slopes to modify this solution and to adjust it to geometries typical for levees. As a consequence, the equation is defined using the effective porosity as an attribute of the porous media. The effective porosity is a parameter used in hydrology and groundwater flow and defines the porosity which is available for the flow of water. As such, the effective porosity is always smaller than the physical porosity and reduces with increasing specific surface of the soil reaching a minimum for clayey soils.

Another easy to apply method developed by Erb (1965) is based on a simplified continuity approach. The seepage area within the levee is considered as a triangular area with the upstream side slope and the base as given sides and the phreatic surface with the intersection at the water table as the movable third side. The infiltration depth is calculated based on Darcy with the gradient defined by the infiltration depth at half-way the height of the water table and the hydraulic head given by the water table itself. The infiltration area is defined by the length of the intersection point between phreatic surface and the point at half-way the side length of the infiltration depth at the base. The equation is valid as long as this length decreases with increasing infiltration depth. This simple continuity approach allows the introduction of the air-filled porosity as the characteristic of the pore space driving the movement of the water.

An accurate, but difficult to apply method, was developed by Cedergren (1988) called the "Transient Flow Net Method". At every time step a phreatic surface is guessed and the flow net is constructed. Only when the flow net satisfies all constraining conditions both, the flow net and thus the phreatic surface, are considered to be correct. Cedergren (1988) verified his method with Hele-Shaw experiments and achieved a very good agreement. Huang (1986) generalised the result of the Hele-Shaw experiment of Cedergren and published a solution for levees with an inclination of 1:2. Both methods, from Cedergren and Huang, use the effective porosity for calculating the transient seepage.

Most analytical methods are based on a simplified one-dimensional consideration of the progress of a seepage front. The resulting equation Eq. (1) defines the time required for the phreatic surface to reach a certain infiltration depth x at the considered elevation depending on the hydraulic conductivity k, the air-filled porosity n_a and the water level h as the driving hydraulic head:

$$t(x) = \frac{1}{2}\frac{n_a}{k}\frac{x^2}{h} \tag{1}$$

Eq. 2 representing the same relationship describes the temporal evolution of the phreatic surface in the considered elevation of the levee:

$$x(t) = \sqrt{2\frac{k}{n_a}h \cdot t} \tag{2}$$

Szalay (1961) used this approach in combination with a sinusoidal flood wave to derive closed-form solutions for the phreatic surface within a homogeneous levee body. Davidenkoff (1964) and Kézdy (1976) extended Eq. (1) by the matric potential (ψ in [m]) as an additional potential driving the flow of water (($h+\psi$) Eq. 3). While Kézdy considered a sudden rise of the water table, Davidenkoff even introduced the time-dependence of the flood wave in his solution.

In order to indirectly take into account the two-dimensionality of the flow condition in the solutions given in Eq. (1) and Eq. (2) Brauns (1999) introduced a mean flow length for calculating the infiltration depth of the phreatic surface (see Figure 1). Instead of simply taking the horizontal distance between upstream side slope and the phreatic surface, he used the distance between the mid-point of the water level at the upstream side slope and the intersection between phreatic surface and waterproof base as mean infiltration length. Assuming a sudden rise of the water table and taking into account matric potential ψ as an additional potential for driving the water flow Eq. (1) and Eq. (2) modify into Eq. (3) and Eq. (4), respectively:

$$t(x) = \frac{1}{2}\frac{n_a}{k}\frac{x^{*2}}{h+\psi} \tag{3}$$

$$x^*(t) = \sqrt{2\frac{k}{n_a}(h+\psi) \cdot t} \tag{4}$$

With

$$x^* = \sqrt{\left(b - \frac{h}{2}m_w\right)^2 + \frac{h^2}{4}} \tag{5}$$

The modified version of the approach after Brauns (1999) considers with the matric potential as another important parameter in the calculation of the transient seepage through levees, and through the calculation of the mean flow length even the geometry of the levee is included. The only restricting condition of this approach is the assumption of a sudden rise of the water table, which is a rather conservative assumption.

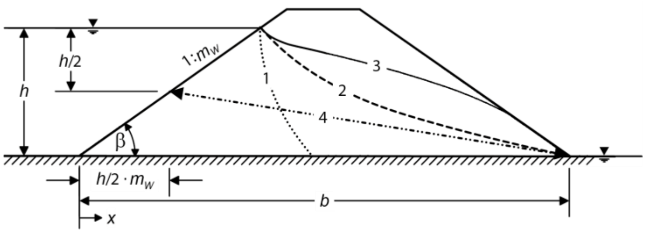

Figure 1 Analytical solution after Brauns (1999) for the transient seepage through levees due to sudden rise of water table. 1 temporal phreatic surface, 2 phreatic surface reaching downstream side toe, 3 phreatic surface at steady state, 4 mean flow length for phreatic surface reaching downstream side toe

2.2 Experimental investigations

The investigation of the transient seepage through structures that are built of earth is connected to complications as the processes involved, which are taking place at unsaturated conditions, are connected to an internal length scale, which is the pore size distribution of the porous medium. A manifestation of this length scale is the capillary fringe, which can be considered constant at equilibrium condition for a given soil. The capillary fringe as a height of water sucked into the porous medium can be used as a proxy for the matric potential ψ acting as a driving force for the movement of the seepage face. Because of this reason, it is imperative to use physical models which are large enough for the seepage processes involved not to be dominated by the soil water characteristics of the used soil.

Because of this reason, investigation on the influence of the initial condition on the transient seepage through levees was conducted on a full-scale levee model (Figure 2). The model was built in a basin sealed with a HDPE sealing to ensure water-proof conditions in the base. The height of the model was 3.5 m and the length along the crest 22 m. The inclinations of the slopes were 1:2.0 and 1:2.25 on the upstream and downstream side, respectively. The model was built out of sand with a particle size of 0.2 mm to 2 mm with a toe drain. A 20 cm thick top soil layer prevented the model from drying out maintaining even during summer a minimum water content around the residual water content of 4 vol%, which is – based on the mean porosity of the model of 37 % - approximately 11 % saturation.

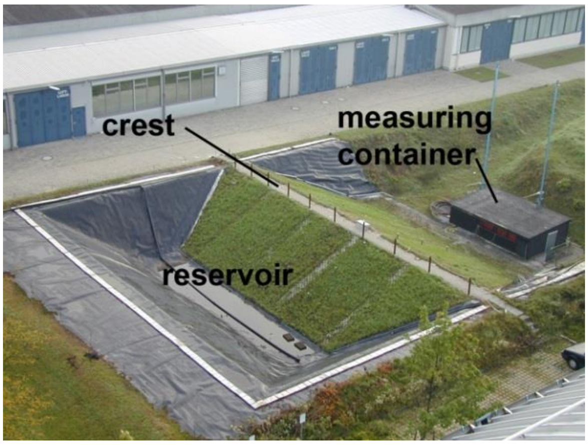

Figure 2 Full-scale levee model at the area of the Federal Waterways and Research Institute in Karlsruhe, Germany

The drained volume of water from the model was measured in a measuring container. The model was further equipped with temperature sensors and pressure gauges distributed along the base of the model and within the levee body. For characterising the unsaturated hydraulic conditions of the levee material, tensiometers were placed below the crest to measure matric suction at five depths. Furthermore, a novel electromagnetic measurement system called spatial Time Domain Reflectometry was installed at the model. Twelve flat ribbon cables with different lengths were installed at different positions in the cross-section of the model. With this system it was possible to measure water content distributions within the levee model also when the reservoir was filled with water with temporal resolution of 5 minutes and an accuracy of ± 2 vol% volumetric water content. The position of the phreatic surface could be measured with an accuracy of ± 2 cm. Further information on the levee model and the used measurement systems can be found in Scheuermann et al, (2009), Scheuermann & Bieberstein (2007) and Scheuermann et al. (2001).

Besides of long-term observations, three different flood simulation tests have been conducted at the model with varying initial conditions for the initiation of the transient seepage. In December 2000 a test was conducted starting from natural water content conditions. The mean saturation was 24% with increased water contents just below the top surface. In May/June 2001, an extreme weather event with three individual rain events was simulated which is considered to occur once every 100 years in the region where the model was located. In total 148 mm of water has been irrigated over the area of the model within 72 hours. The mean saturation within the levee body was 35% with most of the water stored in the upper 1 m to 1.5 m below the ground surface. Finally, in July 2001 a flood event with two flood waves was simulated. The water table within the reservoir was lowered as soon as the water has reached the drain at the downstream side toe and was increased again after approximately 8 hours. The resulting water content distribution was very different to the one in May/June 2001 with more water stored at the base of the model while the mean saturation was quite similar to the natural condition reaching in average 32%.

The actual flood test was conducted for all tests in the same way. The water level was raised monotonically over approximately 12 hours to a height of 2.6 m and kept constant over night before the water level was raised to the maximum height of 3.1 m. Because of the relatively high hydraulic conductivity of the levee material of $2 \cdot 10^{-4}$ m/s the water reached the drain relatively fast during the first rise of the water table. Figure 3 shows the movement of the seepage face along the base of the model for all three flood simulation tests. The symbols represent the measured values using pressure gauges installed in the base of the model, and the lines are fitted. Since the measurements have been conducted at different seasons with different temperatures of the water, the resulting curves had to be corrected to represent the transient seepage for a temperature of the water of 10°C.

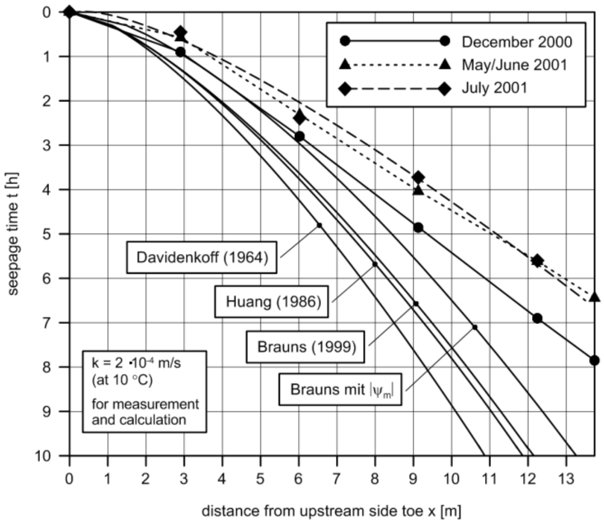

Figure 3 Comparison of flood simulation tests conducted at the levee model together with solutions of analytical models applied to the flood simulation test conducted in December 2000

The comparison of the measured curves shows clearly the accelerating influence of the changed initial conditions due to the applied scenarios. The seepage time for the water front to reach the downstream side drain was for the tests conducted in the summer with increased initial water contents approximately 80 minutes faster, which corresponds to an acceleration of 18 %. It is surprising that the precipitation event has caused the same effect as the simulation of a double flood wave. With another soil used for the model characterised by another water retention behaviour this result might have been completely different.

Four analytical methods have been used for back analysing as exact as possible the test conducted in December 2000. Exact values describing the test condition were applied for the free parameters of each used method. Instead of a sudden rise of the water table, the exact hydrograph of the rise of the water table in the reservoir was applied, and the movement of the seepage front was incrementally calculated. The comparison shows that none of the analytical methods could match the observations. Only the result of the modified method after Brauns (1999) corresponds well with observations for the upstream half of the levee. If a sudden rise of the water table would have been used with a height of the water table of 2.6 m (water table reached after first filling) the seepage time would have been 7 hours 20 minutes, which is slightly faster than the actual observation.

3. NUMERICAL STUDY ON LONG-TERM BEHAVIOUR

3.1 Geometry and parameters

The flood simulation tests conducted at the levee model show clearly the influence of the initial condition with respect to the water content distribution on the transient seepage through the levee body. However, in order to be able to provide more detailed information on this influence, results from long-term observations are necessary which can be analysed in a way to create statistical relationships. From the probability theory point of view, the seepage time for the water to reach the downstream side slope in the case of a flood event can be considered as the resistance that is created by the levee body against the flow of water. This time can be directly compared with the duration of a flood to directly determine the probability of a failure for a given levee under the assumption, the levee fails when the water table reaches the downstream side toe of the slope.

In order to study the long-term behaviour of levees and to determine a probability density function representing the resistance of a levee against flow of water through the structure, a case study was conducted. The geometry of the levee was chosen according to examples from the Elbe River in Germany (Table 1).

Table 1 Example of a levee at the river Elbe (Germany)

Parameter	**Value / definition**
height	3.5 m
width of crest	2 m
inclinations of slopes upstream downstream	 1:2 1:2
soil type	With LL = 48-53% and PL = 23-33% low to high plastic clay (CL-CH) according to USCS Sandy Loam / Loam (SL-L) according to USDA system (USDA, 2003)

According to the Unified Soil Classification System (USCS) low to high plastic soil is usually used for the construction of levees along the Elbe. Hydraulic conductivity and van Genuchten parameters (van Genuchten, 1980) for the drainage curve were chosen based on the pedotransfer function developed by Carsel and Parrish (1988) which uses as entry value for determining the van Genuchten parameters the USDA soil class. The parameters for the wetting curve were determined based on the general definitions defined by Luckner et al. (1989) regarding the relationship between drainage and wetting curve. The aim of the study was to be able to represent the retention behaviour of the soil as realistic as possible, which is why hysteresis was considered in the calculations. The soil water characteristics with van Genuchten parameters are given in Figure 4.

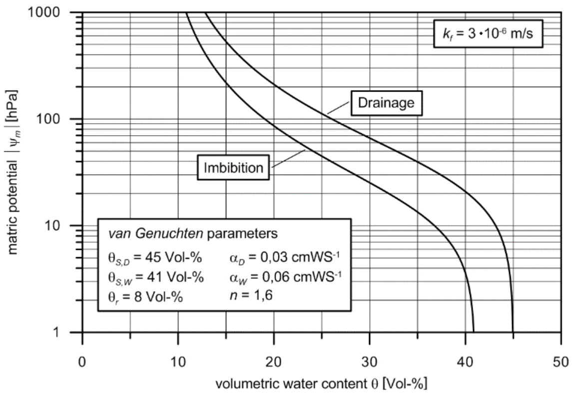

Figure 4 Soil water retention curves (drainage and imbibition) of the example levee at the river Elbe

3.2 Computational model, meteorological data and procedure

Simulations have been conducted using the numerical tool HYDRUS-2D, which solves Richard's law (1931) representing flow of water under partly saturated conditions (Simunek et al., 1999). The model allows the parameterisation of the soil water retention curve using different models such as van Genuchten (1980) and Brooks and Corey (1964). The model after Kool and Parker (1987) is used for simulating hysteresis, which requires the parameterisation of the main drainage and main wetting curves using the same parameters describing the shape of the curve (n-parameter) and residual water content in the van Genuchten parameterisation. In terms of boundary conditions, it is possible to simulate constant and time variable hydraulic head as well as meteorological conditions, which are imported into the model as time series of precipitation and potential evaporation. Actual evapotranspiration is then calculated from the simulated water contents in a pre-described root zone for a chosen vegetation cover. For the definition of the meteorological conditions 27 years (1964 to 1990) of daily measurements of precipitation and weather data were available (see topmost graph in Figure 5). Potential evaporation was calculated based on the well-known Penman-Monteith model (Monteith, 1965).

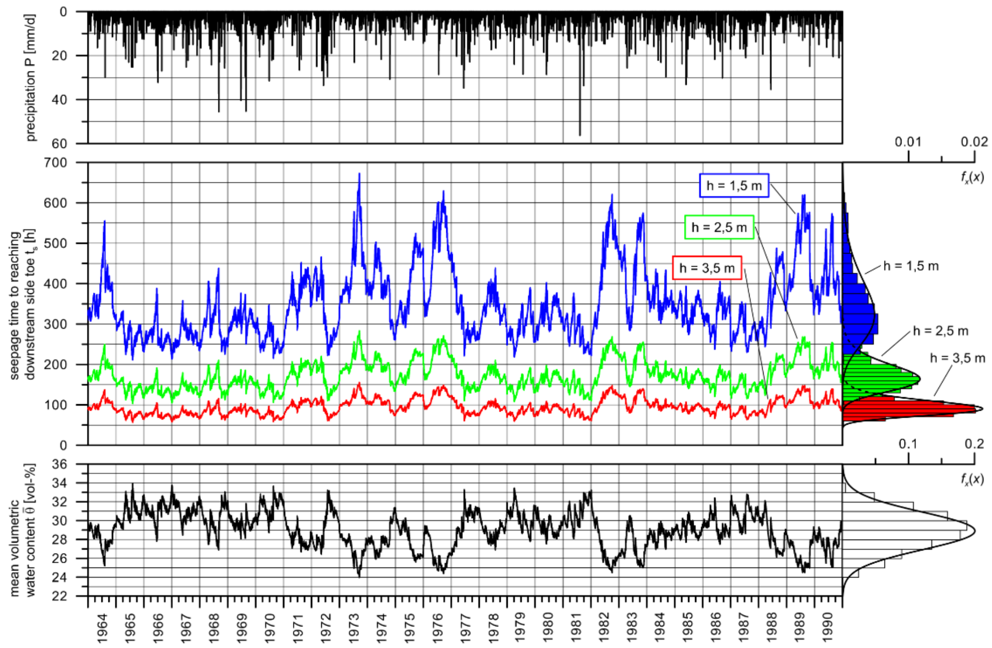

Figure 5 Top graph: daily precipitation events over 27 years from 1964 to 1990; bottom graph: time series of mean volumetric water contents with histogram and density function (right); graphs in the middle: seepage time required to reaching downstream side toe for three different levels of the water table (1.5m, 2.5m and 3.5m)

The procedure for conducting the simulations involved several working steps:

- In a first step, the initial conditions for the actual simulation in terms of water content distribution and matric suction need to be pre-conditioned by simulating one year of meteorological data from 1963.
- The actual simulations started with the year 1964. A data set of one year was simulated in a row with a representative water content distribution saved for every day. The final condition in terms of water content distribution at the end of the simulation was then used as initial condition for the subsequent simulation of the next year until all years were simulated. For simplification, a mean water content was calculated from the distribution for every simulated day (bottom graph in Figure 5).
- For randomly selected days, water content distributions were chosen and taken as initial condition for a flood simulation test using a sudden rise of the water table. The chosen mean water contents covered a wide range from the minimum (just below 24 vol%) to the maximum calculated water content (just below 34 vol%). In total five different water levels were simulated (1.5, 2.0, 2.5, 3.0 and 3.5 m), and the seepage time required to reach the downstream side tow was determined. A fitting function was developed for each water level (Figure 6) describing the time for the water front to reach the downstream side toe in dependency of the initial mean water content.
- The fitting functions developed from the flood simulation calculations were finally used to directly calculate for every mean water content the time required for the seepage front to reach the downstream side toe (graph in the middle of Figure 5).

Using this procedure it was possible to calculate effectively for the 27 years of meteorological data not only the mean water contents within a representative levee for the river Elbe, but also the seepage times to be expected when the levee would be suddenly hydraulically loaded by a defined water table.

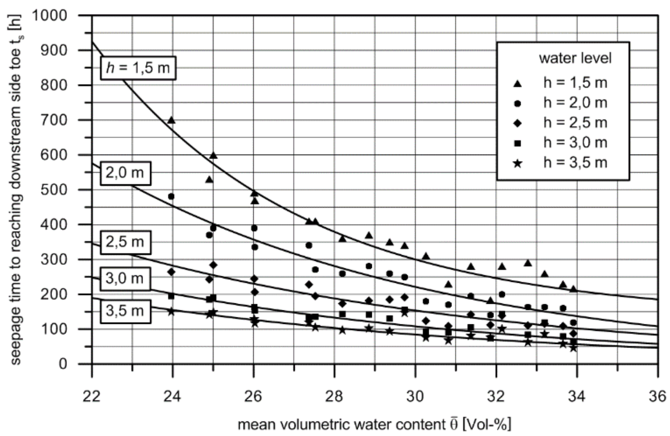

Figure 6 Relationship between time of the seepage face required to reach the downstream side toe and mean volumetric water content

3.3 Results and discussion

The dataset created with regard to the mean volumetric water content can be statistically analysed. As can be seen at the curve on the right side of the bottom graph of Figure 5, the resulting probability density function characterising the mean water content can easily be described using a normal distribution. The range of water contents span over a minimum of 24 vol% to a maximum of 34 vol%. The mean water content determined for a given day is the result of all meteorological and hydrological conditions acting on the levee over a certain period of time. Because of that reason, very wet years create water content distributions with high mean water contents and vice versa (Figure 7).

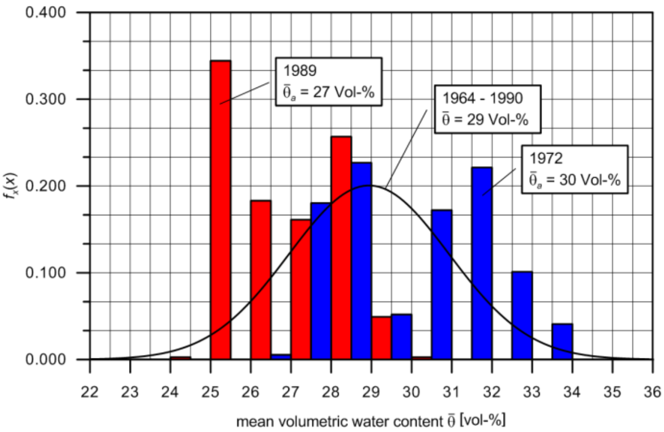

Figure 7 Examples of histograms (1% class) of mean volumetric water contents for an extreme dry (1989) and an extreme wet year (1972) in comparison to the long-term distribution over the 27 years

The water content distribution within the levee defines the resistance of the levee against flow through the levee body. Equations Eq. (1) and Eq. (3) show clearly that the air content expressed as air-filled porosity n_a – or the volume fraction, which will be exchanged by water – is decisive for the time the seepage front requires to reach the toe of the downstream side slope.

The relationships of figure 6 for different water levels are used with the time series of the mean water content to calculate the seepage time required to reach the downstream side toe. The graph in the middle of Figure 5 shows the time series of this seepage time for the water levels h = 1.5 m, 2.5 m and 3.5 m. The histograms with a fixed number of classes for these curves are shown on the right side together with the log-normal probability density function describing best the histograms. Figure 8 shows the probability density functions for all considered water levels.

Two main conclusions can be drawn out of these graphs: (i) The variability of the seepage time reduces dramatically with increasing water level. The reason for this reduction in variability becomes visible through Eq. (3). The drivers for the water flow are the hydraulic head created through the water level and the matric potential. With increasing water level, the influence of the matric potential on the flow of water reduces, which results in the reduced variability. (ii) The main conclusion of this exercise however is that for a given levee – including all its features, such as geometry and material – the initial water content distribution (here expressed through the mean water content) has a tremendous influence on the time required for the seepage front to reach the downstream slope. As can be seen in Figure 8, there is a large overlap between the curves indicating that the seepage time can be faster for a lower water table when the mean initial water content is higher compared to a higher water table with lower initial mean water content. This result means that the meteorological and hydrological pre-history of a levee has a huge influence on the seepage time and needs to be considered when seepage is analysed. The probability density functions determined in this manner can finally be used together with probability density functions of a specific river for the duration of a certain water table to determine the probability for the phreatic surface to be completely created up to the downstream side slope.

However, one needs to keep in mind that a sudden rise of the water table is considered in the presented study. Furthermore, the influence of the distribution of water is completely neglected. It can be possible, that the spatial distribution of water within the levee body plays a role as well in the seepage through the body of a levee. But, the study of this question would require further numerical investigations.

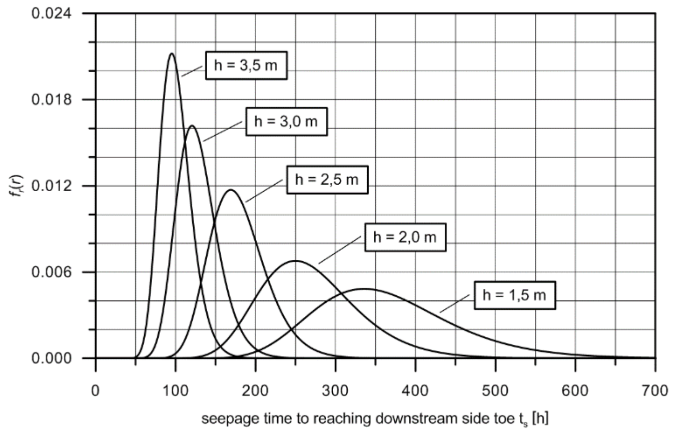

Figure 8 Density functions for the seepage time required to reach the downstream side toe as a consequence of a sudden rise of the water table

4. ESTIMATION OF REPRESENTATIVE MEAN INITIAL WATER CONTENTS

4.1 Natural conditions

Against the background of these results the question arises how the initial conditions in terms of mean water content and matric suction can be chosen to calculate realistic seepage times using equation Eq. (3). For conditions not directly influenced by precipitation one can take advantage from the known soil water retention curve and the definition of the field capacity. The field capacity describes the volume fraction of water, or volumetric water content, respectively, held in the pore structure against gravity. These water contents can be derived from the soil water retention curve by reading the volumetric water content at the lower boundary for the field capacity (pF 1.8 or 63 hPa) and at the upper boundary (pf 2.5 or 316 hPa). These matric suctions can then be used together with the corresponding water contents in equation Eq. (3) to calculate the time required for the seepage front to reach the downstream slope. Table 2 shows the results for the given example of a levee defined in Table 1 and Figure 4.

Table 2 Calculation of seepage time through example levee based on natural conditions (time t in [hours])

	Drainage (pF 1.8)	Drainage (pF 2.5)	Imbibition (pF 1.8)	Imbibition (pF 2.5)
ψ [m]	0.63	3.16	0.63	3.16
θ [vol%]	30.5	17.5	22.2	13.6
n_a [-]*	0.145	0.275	0.228	0.314
t(h=1.5m)	93.4	151.8	146.9	173.3
t(h=2.0m)	90.2	145.9	141.8	166.5
t(h=2.5m)	87.0	140.0	136.8	159.8
t(h=3.0m)	83.8	134.2	131.8	153.2
t(h=3.5m)	80.7	128.5	126.9	146.7

*calculated with θ_s = 45 vol%

4.2 Condition after long-lasting substantial precipitations

The mean volumetric water contents can be increased above the values given in Table 2 when long-lasting substantial precipitation occurs shortly before and during the flood event. Such conditions can be estimated based on meteorological data created for different climate change scenarios for the considered climate region. In this case, the initial conditions can be determined based on the effective infiltration caused by the rain event. A simplified assumption can be that all precipitation infiltrates into the levee, which means the rate of precipitation can directly be related to the saturated hydraulic conductivity. Figure 9 shows the curves describing the unsaturated hydraulic conductivity for both, imbibition and drainage curve. Assuming a constant precipitation rate i_P below the saturated hydraulic conductivity, the saturation in the levee material would increase to a value capable of transferring the infiltrating water. As a result the unsaturated hydraulic conductivity k_u would take over the value of the precipitation rate.

Table 3 shows results of calculations for the seepage time based on this approach of determining the initial conditions. The precipitation rates considered are chosen in a way to increase the volumetric water content above the ones defined by the field capacity.

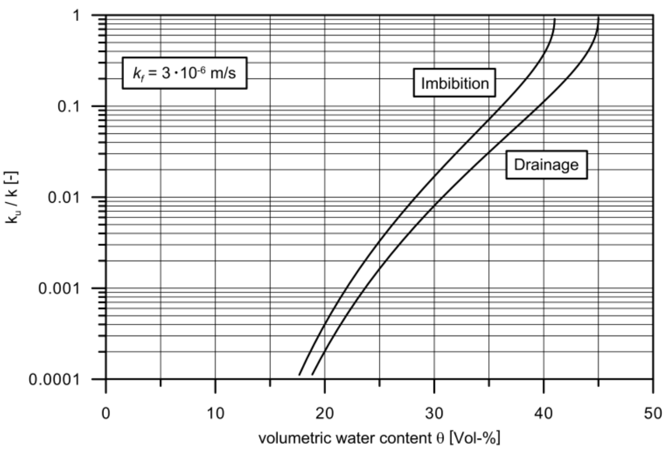

Figure 9 Unsaturated hydraulic conductivity (drainage and imbibition) of the example levee at the river Elbe

Table 3 Calculation of seepage time through example levee based on conditions after and during long-lasting substantial precipitation (time t in [hours])

	Drainage (f = 0.05)$^+$	Drainage (f = 0.1)$^+$	Imbibition (f = 0.05)$^+$	Imbibition (f = 0.1)$^+$
i_P [mm/d]	13	26	13	26
ψ [m]	0.31	0.22	0.16	0.11
θ [vol%]	37	39.5	33.8	36.1
n_a [-]*	0.08	0.055	0.112	0.089
t(h=1.5m)	52.7	36.4	74.5	59.4
t(h=2.0m)	50.9	35.2	72.0	57.4
t(h=2.5m)	49.1	34.0	69.5	55.4
t(h=3.0m)	47.3	32.8	67.0	53.4
t(h=3.5m)	45.6	31.6	64.6	51.6

*calculated with θ_s = 45 vol%

$^+ f = k_u / k$

4.3 Discussion

The results from Tables 2 and 3 are all either on the faster end of the distributions shown in Figure 8 for the different water tables or provide even faster seepage times. The mean volumetric water contents from Figure 5, which were numerically calculated, cover a range represented by the field capacity of the levee material. The naturally influenced initial mean volumetric water content can thus be easily estimated based on the field capacity. Equation Eq. (3) provides in this connection low seepage times and thus a result on the safe side.

Obviously, the extreme case considered in Table 3 was not included in the numerical simulation. This would require additional numerical calculations on a smaller time-scale with higher resolved data concerning meteorology and water level. Nevertheless, the method to determine initial mean volumetric water contents based on the relationship between unsaturated and saturated hydraulic conductivity k_u / k under the assumption k_u corresponds to the precipitation rate i_P works satisfactorily well. The corresponding seepage times calculated with Eq. (3) are all faster than the numerically calculated values. In this connection, the values for precipitation rates can be determined based on predefined climate change scenarios in combination with in future expected flood situations.

Assessing the results of this study one has to keep in mind that Eq. (3) is a simplification of a complex at least two-dimensional problem. The two-dimensionality is taken into account by the mean flow-length defined by Eq. (5). As can be seen at the low variability of the seepage times for different water levels, the two-dimensionality is only partly represented by this mean flow length. However, the resulting seepage times give a good estimate of the seepage times to be expected for extreme meteorological conditions.

5. CONCLUSIONS

In conclusion to the presented study, the following findings can be summarised:

- There are several analytical methods available for estimating the transient seepage through homogeneous levees. The modified method after Brauns (1999) takes into account the two-dimensional nature of the flow field and the matric potential as additional driver for the flow through the levee.
- Experimental investigations have proven the accelerating effect of an increased initial moisture content distribution on the transient seepage.
- A study of long-term observations using numerical simulations has clearly shown that under otherwise constant conditions with respect to levee geometry and material, the initial water content has a tremendous influence on the resulting transient seepage. The influence is that significant that small water levels can already lead to a fast flow through a levee, even faster than higher water levels when the initial water content is lower.
- The modified method after Brauns (1999) can be used to realistically assess the transient seepage through levees when realistic assumptions are made in terms of the initial conditions.
- Initial conditions can be either assessed based on the definition of the field capacity and the soil water retention curve of the soil to represent natural conditions, or based on precipitation events representing an effective infiltration also for extreme scenarios influenced by climate change.

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