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Numerical simulations on the effect of geosynthetic drainage elements on the seepage of road embankments

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ABSTRACT

The use of recycled building materials, industrial by-products and slightly contaminated soils in road constructions becomes more popular, however the amount of seepage has to be minimized in order to protect the soil and groundwater. The German Association for Research on Road Construction and Traffic Affairs (FGSV) has developed different methods regarding the construction of road embankments using such materials. By construction method E only a drainage mat is applied over the core, without additional sealing elements. To minimize the seepage, the saturated permeability of the core material should be relatively low. In order to evaluate the effectiveness of this method and to verify the contribution of drainage layers in minimizing the seepage of road embankments, 2D numerical simulations were performed using VADOSE/W for a road embankment with and without a drainage layer. Climate data from the area of Munich Airport (average annual precipitation of 699 mm) was used for the calculations. Different soils, recycled building materials, municipal solid waste incineration ashes and a steelwork slag were modelled as core materials. The results have shown that a reduction of the core seepage of at least 30 % can be achieved by using a drainage layer. Moreover, the amount of seepage is not directly related to the saturated permeability of the core material, but depends mainly on the hydraulic conductivity in unsaturated state.

Keywords: modelling, embankment, seepage, unsaturated hydraulic conductivity

1 INTRODUCTION

In recent years the use of recycled materials, industrial by-products and slightly contaminated soils has been increased, not only due to social, economic and environmental reasons, as it contributes to the reduction of costs, the conservation of natural resources and soils and the reduction of the materials that have to be stored in landfills (Department of Transport and Main Roads, 2020), but also due to the fact that in Germany it is imposed by a national regulation (implementation of the European Waste Framework Directive 2008/98/EG with the amendment of Circular Economy and Waste Management Act in 2012 (KrWG 2012)).

However, these materials can be used in road embankments only when specified contaminant concentrations are not exceeded and technical safeguards regarding the protection of soil and groundwater are considered. The German Association for Research on Road Construction and Traffic Affairs (FGSV, 2017) has developed various methods for the construction of embankments using such materials (MTSE). The design principle of such earth structures is to minimize the amount of water flowing through the embankment core by typically using mineral or geosynthetic barriers. In construction method E according to MTSE however, the core is only covered by a drainage mat, without additional sealing elements (Figure 1). To minimize the amount of infiltration in core, requirements on the maximum coefficient of saturated permeability were defined in the recommendations of MTSE ($k_{sat} \leq 1 \cdot 10^{-8}$ m/s).

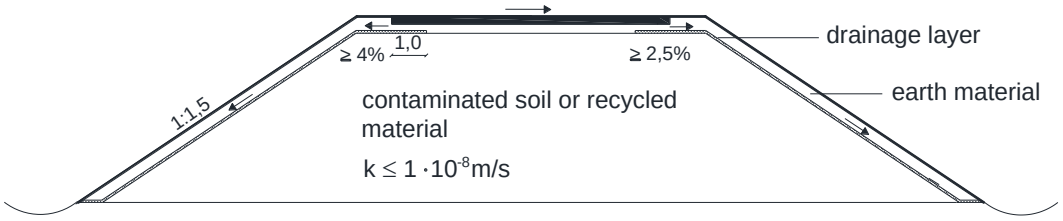


Figure 1. *Construction principles of method E (FGSV, 2017)*

Schweller et al. (2009) investigated the efficiency of construction method E by conducting numerical simulations on an embankment built according to this method. For the simulation a constant infiltration rate was applied at the shoulder and slope. As the processes of evaporation and transpiration were not taken into account, the computed amount of seepage was overestimated and unrealistic. Michaelides et al. (2013) repeated the simulations using climate data from the area of Munich Airport and taking into account the surface processes. The results have shown that method E can be used for core materials with a saturated permeability of less than $1 \cdot 10^{-8}$ m/s. However, due to the lack of information regarding the hydraulic properties of secondary materials at the time of the research, the core was modelled using hydraulic parameters of soils. The unsaturated hydraulic properties of recycled materials and industrial by-products were experimentally investigated by Scharnagl & Durner (2014). Using a combination of the simplified evaporation method, the dew point method and constant head permeability tests the hydraulic properties of different materials were determined over a wide suction range. Similar to the findings by Gomez et al. (2014), their results show that these materials usually demonstrate bi-modal pore structures, which can cause significantly different hydraulic properties compared to natural soils. According to these findings the numerical investigations by Michaelides et al. (2013) are not necessarily representative for secondary materials.

Thus, in order to verify the effectiveness of construction method E when using secondary materials and to investigate the influence of drainage layers in the water balance of road embankments, numerical simulations were conducted on a road embankment under consideration of the unsaturated hydraulic properties determined by Scharnagl & Durner (2014). Two different geometries were considered in the simulations: 1) a road embankment according to method E with a drainage layer and 2) a standard road embankment without a drainage layer. Simulations were performed for eight different core materials: three soils, two recycled building materials, two municipal solid waste incineration ashes and one steelwork slag.

2 SIMULATIONS

2.1 Program

The Finite-Element software VADOSE/W from GEO-SLOPE was used for the simulations. This program can be used to model the water flow in saturated and unsaturated materials under stationary or transient conditions. The processes taking place on the soil surface (evaporation, transpiration, infiltration and runoff) can be computed by VADOSE/W based on the applied climate boundary condition and the soil properties (water content, suction). The water flow is calculated in both the liquid and vapour phase.

2.2 Model geometry

For the simulations a 4 m high road embankment was considered. The height of the dam core from the subsoil to the base is 3.2 m and the thickness of the upper layers is 80 cm (54 cm frost protection layer and base layer and 26 cm pavement layers). The road shoulders are 1.5 m wide and have an inclination of 12 %. The inclination of the embankment is 1:1.5 and the thickness of the topsoil is 20 cm. In order to reduce the calculation time only one half of the embankment was modelled. The pavement layers were assumed impermeable and were not included in the model.

Based on the above geometry, two basic models were created (Figure 2). In basic model 1 technical safeguards according to construction method E were considered. Similar to the numerical simulations by Michaelides et al. (2013) the drainage mat between the core material and the topsoil was modelled as a 20 cm thick layer. Compared to the actual thickness of geotextile drainage mats of only about 1

cm, the drainage layer was modelled much thicker to avoid FE mesh distortions and resulting numerical instabilities. In basic model 2 no technical safeguards were taken into account.

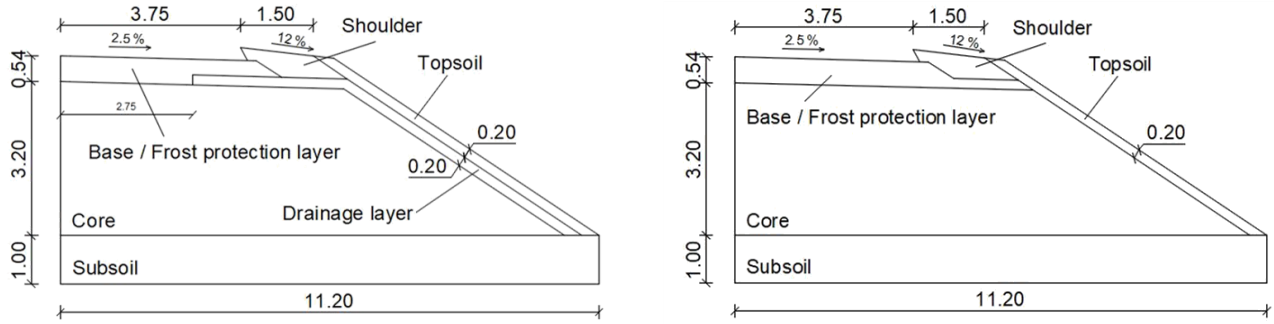


Figure 2. *Geometry of basic model 1 (left). Geometry of basic model 2 (right)*

The generated finite element mesh consists of 4.648 mainly quadratic elements and was refined in the area of the shoulder, topsoil and drainage layer, since the main water content variations are expected in these areas. In addition, the mesh was refined along the layer boundaries, as the material properties can significantly differ between the layers (Figure 3).

2.3 Boundary and initial conditions

The boundary conditions applied for both models are shown in Figure 4. A head boundary condition of -1 m was applied at the bottom of the model. It corresponds to the position of the assumed highest groundwater level and allows the free drainage of the core. The right and left side of the model and the road surface were considered impermeable. On the shoulder and the topsoil a climate boundary condition was applied. Meteorological data from the area of Munich Airport from October 1, 1992 to December 31, 2002 provided by the German Meteorological Service (DWD) was used. The average annual precipitation in this area is 699 mm.

The runoff from the road surface (assuming a width of 7.5 m) was calculated based on the curves by Bürger et al. (2008) and was modelled as additional precipitation distributed homogeneously half on the shoulder and half on the topsoil.

As initial conditions a hydrostatic water pressure corresponding to the defined groundwater level when no evaporation and infiltration take place was applied.

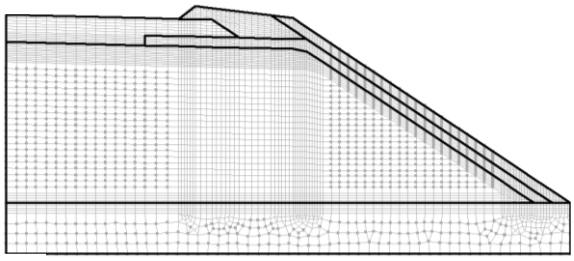


Figure 3. *Finite element mesh*

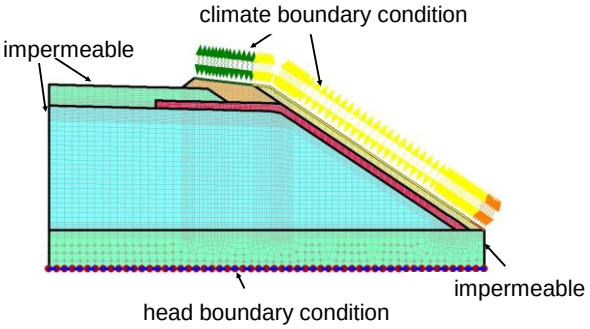


Figure 4. *Boundary conditions*

2.4 Material properties

An overview of the materials used for the topsoil, the shoulder, the base layer and the drainage is given in Table 1 and their hydraulic properties are illustrated in Figure 6.

Table 1. *Overview of the modelled materials for the topsoil, the shoulder, the base layer and the drainage layer*

Material	Classification (DIN 18196)	k_{sat} [m/s]
Topsoil[1]	SU/SU*	$1.0 \cdot 10^{-5}$
Shoulder[2]	GU*	$7.5 \cdot 10^{-6}$
Base and frost protection layer[2]	GW	$1.0 \cdot 10^{-5}$
Drainage layer[3]	(GU)	$5.0 \cdot 10^{-3}$

[1] Hennings (2000), [2] Scharnagl & Durner (2014), [3] Melsbach et al. (2018)

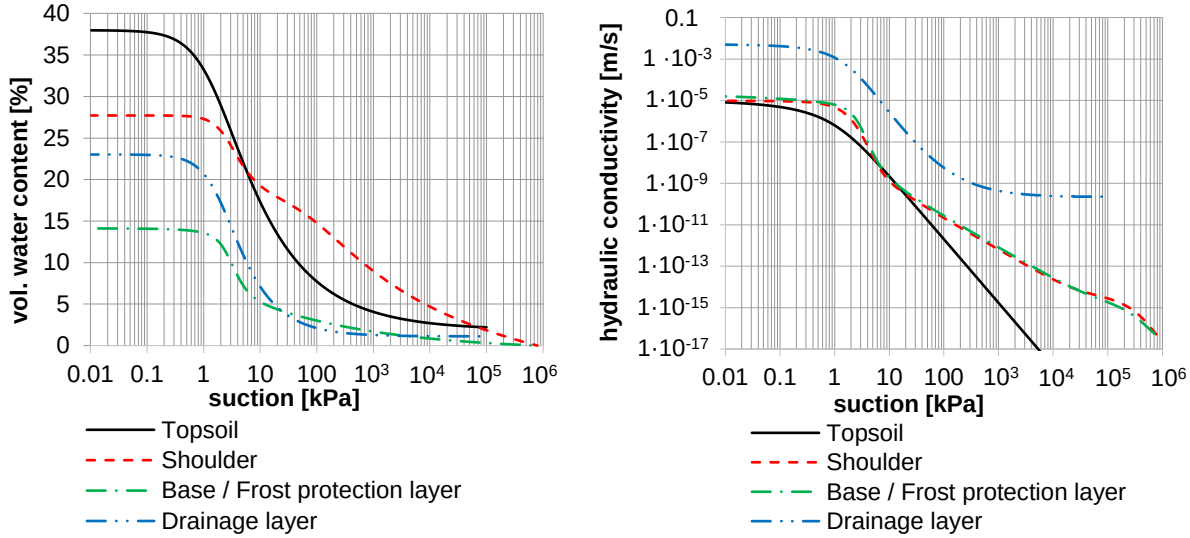


Figure 6. *Soil-water retention curves of topsoil, shoulder, base layer and drainage layer (left). Hydraulic conductivity functions of the topsoil, shoulder, base layer and drainage layer (right)*

For the shoulder and the base layer, the soil-water retention curves and the hydraulic conductivity functions determined by Scharnagl & Durner (2014) on a very silty gravel (soil BM5) and a sandy gravel (soil BM1) were used. The saturated permeability of these materials is $7.5 \cdot 10^{-6}$ m/s and $1 \cdot 10^{-5}$ m/s, respectively.

For the topsoil van Genuchten parameters of a silty sand (Su2) according to Hennings (2000) were applied (Table 2). These values are based on the pedological mapping guidelines and can be considered representative for non-compacted soils in natural state. The saturated permeability of the topsoil was estimated at $1 \cdot 10^{-5}$ m/s.

The hydraulic parameters applied for the drainage layer were selected based on the results of the research project by Melsbach et al. (2018) and are a modification of the parameters determined by Ekblad & Isacsson (2007) on a slightly silty gravel. The saturated permeability was set equal to $5 \cdot 10^{-3}$ m/s (Table 2).

Table 2. *van Genuchten parameters used for the topsoil, the drainage layer and the organic clay*

Parameter	Topsoil[1]	Drainage[2]	OT[3]
k_{sat} [m/s]	$1 \cdot 10^{-5}$	$5 \cdot 10^{-3}$	$1 \cdot 10^{-8}$
θ_{sat} [-]	0.38	0.23	0.65
θ_{res} [-]	0.02	0.01	0.00
A [m^{-1}]	6.80	5.00	0.14
n [-]	1.43	1.79	1.30
m [-]	0.30	0.44	0.23

[1] Hennings (2000), [2] Melsbach et al. (2018), [3] Birle (2011)

For the core eight different materials were considered: three soils, two recycled building materials, two municipal solid waste incineration ashes and a steelwork slag. An overview is given in Table 3 and their hydraulic properties are illustrated in Figure 7.

The hydraulic parameters of the organic soil (OT) were taken from Birle (2011) (see Table 2), while the hydraulic properties of the other materials have been determined experimentally by Scharnagl & Durner (2014). For the simulations, the experimental data was slightly modified at the area of low suction, based on the determined values of saturated hydraulic conductivity.

Table 3. *Overview of the materials modelled for the embankment core*

Core material	Type of material	Fines/Sand/Gravel mass content [%]	Classification (DIN 18196)	k_{sat} [m/s]
BM1[1]	Soil (sandy gravel)	3 / 40 / 57	GW	$1{,}0 \cdot 10^{-5}$
BM2[1]	Soil (very silty, gravelly sand)	27 / 49 / 24	SU*	$6{,}6 \cdot 10^{-8}$
RC2[1]	Mixture of demolished building materials 0/32 mm	6 / 39 / 55	GU	$1{,}8 \cdot 10^{-6}$
RC5[1]	Sieved recycled building material 0/10 mm	13 / 52 / 35	GU	$1{,}2 \cdot 10^{-6}$
HMVA1[1]	Municipal solid waste incineration ash 0/32 mm	2 / 35 / 63	GW	$6{,}4 \cdot 10^{-5}$
HMVA3[1]	Municipal solid waste incineration ash 0/32 mm	6 / 33 / 61	GU	$6{,}3 \cdot 10^{-8}$
SWS[1]	Steelwork slag	14 / 36 / 50	GU	$1{,}2 \cdot 10^{-6}$
OT[2]	Soil (organic clay)	80 / 17 / 3	OT	$1{,}0 \cdot 10^{-8}$

[1] Scharnagl & Durner (2014), [2] Birle (2011)

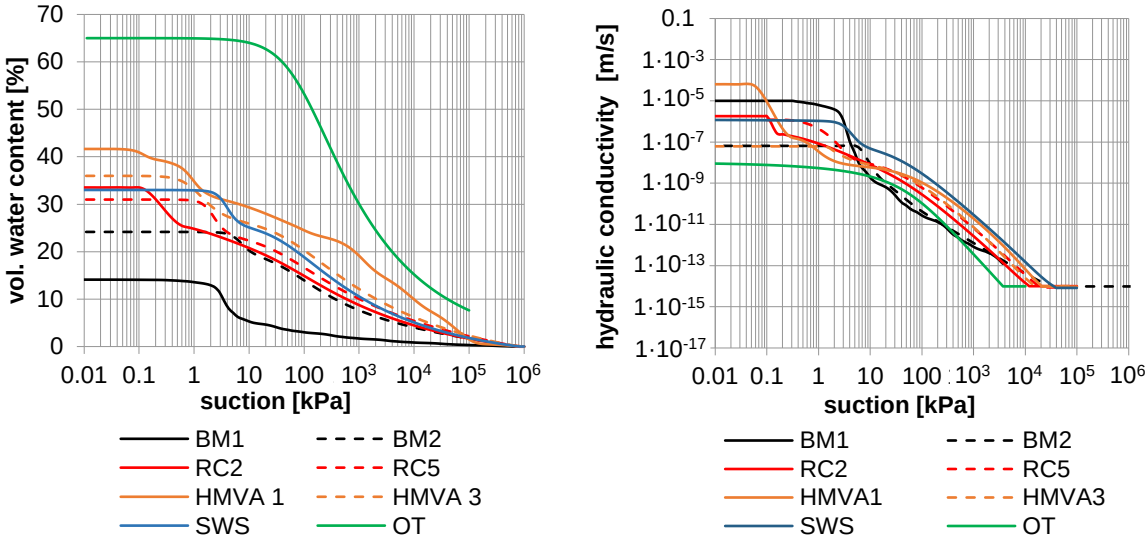


Figure 7. *Soil-water retention curves of the core materials (left). Hydraulic conductivity functions of the core materials (right)*

3 RESULTS

For every model the amounts of surface runoff, evaporation, transpiration, as well as the outflow from topsoil, drainage layer and core were evaluated. All water quantities were computed as percentage of the total amount of precipitation (7160 mm).

3.1 Basic model 1

Figure 8 shows the obtained results for the simulations with basic models 1 (geometry with drainage layer).

As the material properties of shoulder, topsoil and base layer are identical for all simulations, the computed amounts for the surface processes are quite similar for all models. The surface runoff accounts for approximately 10 % of the total precipitation, while the evapotranspiration, which plays a significant role in the water balance of the embankment, varies between 51 % and 55 %. The effective

infiltration, defined as the sum of topsoil, drainage, core outflow and stored water, is of similar magnitude for all core materials and lies between 32.2 % and 38.7 % of the total precipitation.

The outflow from the topsoil is with 1.5 % identical for all simulations. Differences can be seen in the distribution of water between the core and the drainage layer. Except for the simulation with SWS, the outflow from the core is relatively low and varies between 1.4 % for the model with OT and 10.8 % for the model with soil BM2, while the outflow from the drainage layer is between 22.3 % (BM2) and 28.9 % (OT). A relative high amount of core outflow of 20.8 % and a respectively low amount of drainage outflow of 9.5 % was computed for the steel slag.

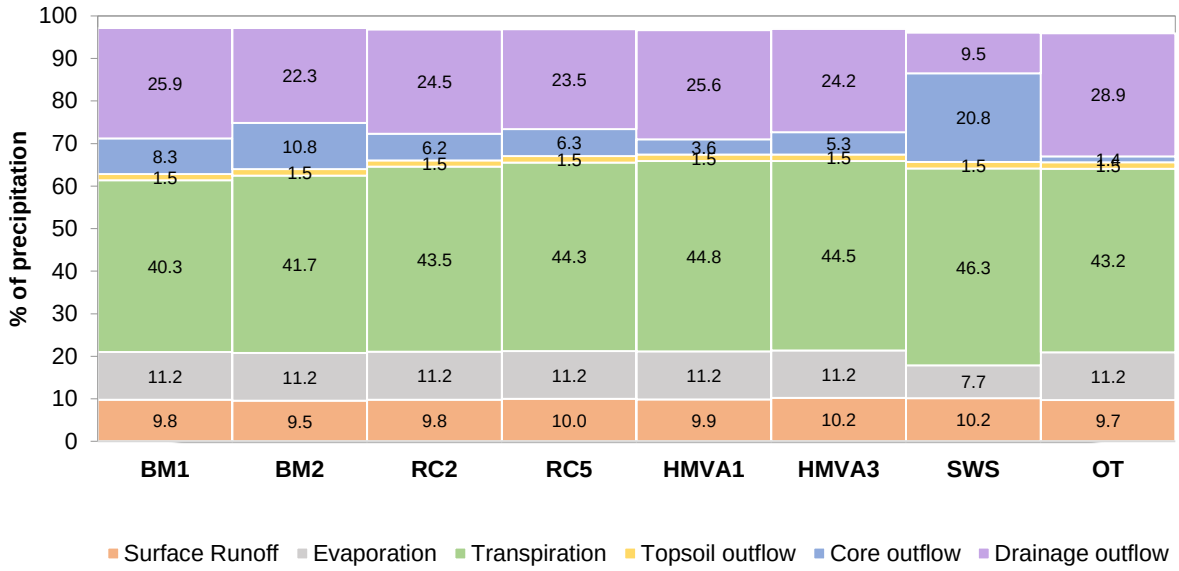


Figure 8. *Comparison of the simulations with drainage layer (basic model 1)*

An analysis of the changes of suction with time at the upper part of the core (at distances of 1 m along the boundary with the drainage layer) has shown that during wetting periods the suctions at this area vary between 6 kPa and 30 kPa (Figure 9). With respect to the hydraulic conductivity functions of the core materials (Figure 10), for suctions higher than 6 kPa the hydraulic conductivity of the steelwork slag is higher compared to the other materials, which could explain the higher core outflow.

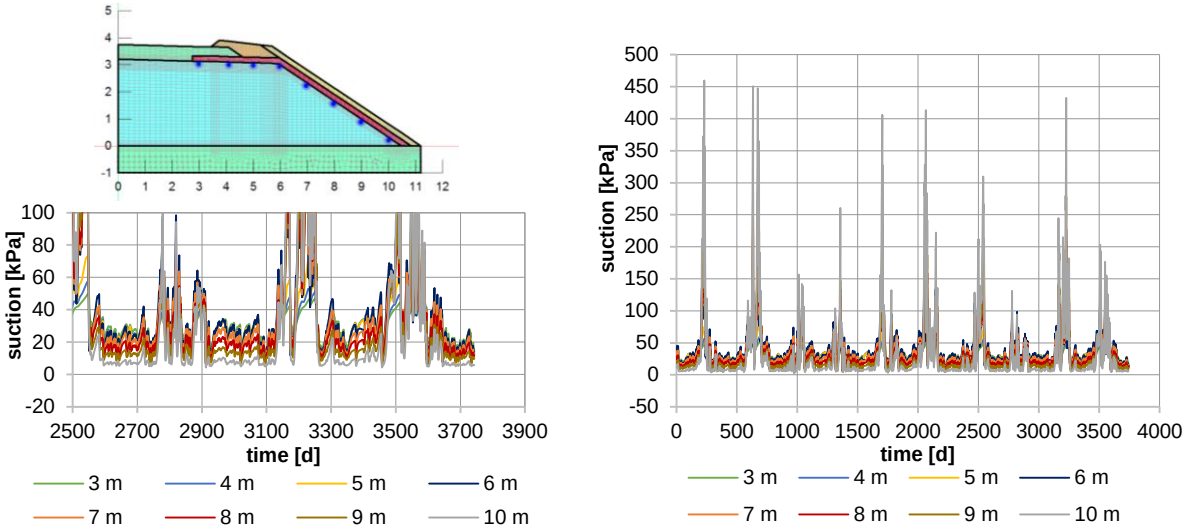


Figure 9. *Changes of suction with time at different positions at the upper part of the core for basic model 1 with steelwork slag*

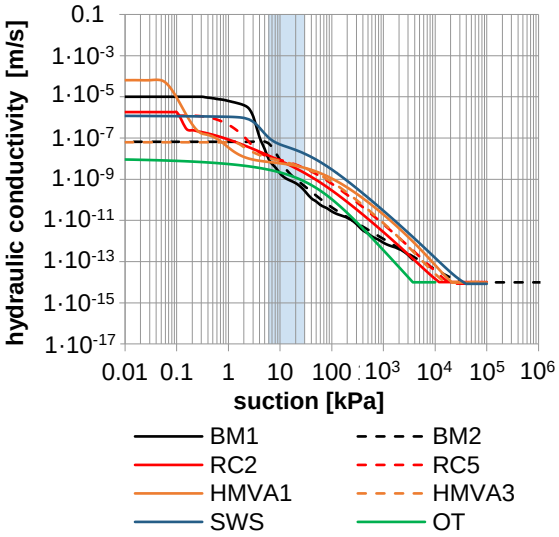


Figure 10. *Range of suctions during wetting periods (blue area) at the upper part of the core for basic model 1*

3.2 Basic model 2

Figure 11 summarises the results of the simulations with basic model 2 without a drainage layer.

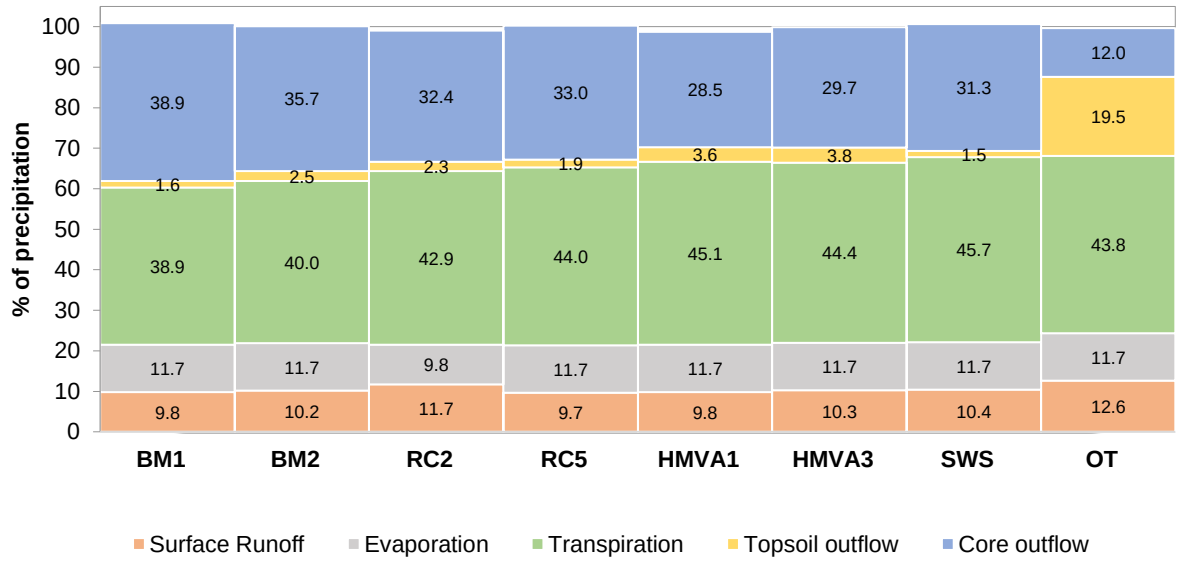


Figure 11. *Comparison of the simulations without drainage layer (basic model 2)*

Similar to basic model 1, the surface processes do not differ very much between the simulations. The surface runoff varies between 9.7 % and 12.6 %, the evaporation is for almost all simulations 11.7 % and the transpiration varies between 38.9 % and 45.7 %. The effective infiltration ranges between 31.9 % for the model with OT and 39.7 % for the model with soil BM1. Except for the simulation with OT, the topsoil outflow is relatively low and varies between 1.5 % and 3.8 %, while the core outflow ranges between 28.5 % and 38.9 %. A big difference can be observed in the model with OT. In this model, the core outflow with 12.0 % is significantly lower and the topsoil outflow with 19.5 % significantly higher in comparison to the other models.

An analysis of the range of suction with time at the upper part of the core (a few centimetres below the boundary to the frost protection gravel or the topsoil at distances of 1 m) has shown that the high infiltration into the core due to the lack of a drainage layer leads to very low to negative suctions and an almost full saturation of the upper part of the core during wetting periods (Figure 12). The coefficient of saturated permeability and the hydraulic conductivity values close to saturation have therefore a more

decisive role (Figure 13) and can explain the relative low core seepage from the organic clay (the only material that fulfills the permeability requirements of construction method E according to MTSE with $k_{sat} \leq 1 \cdot 10^{-8}$ m/s).

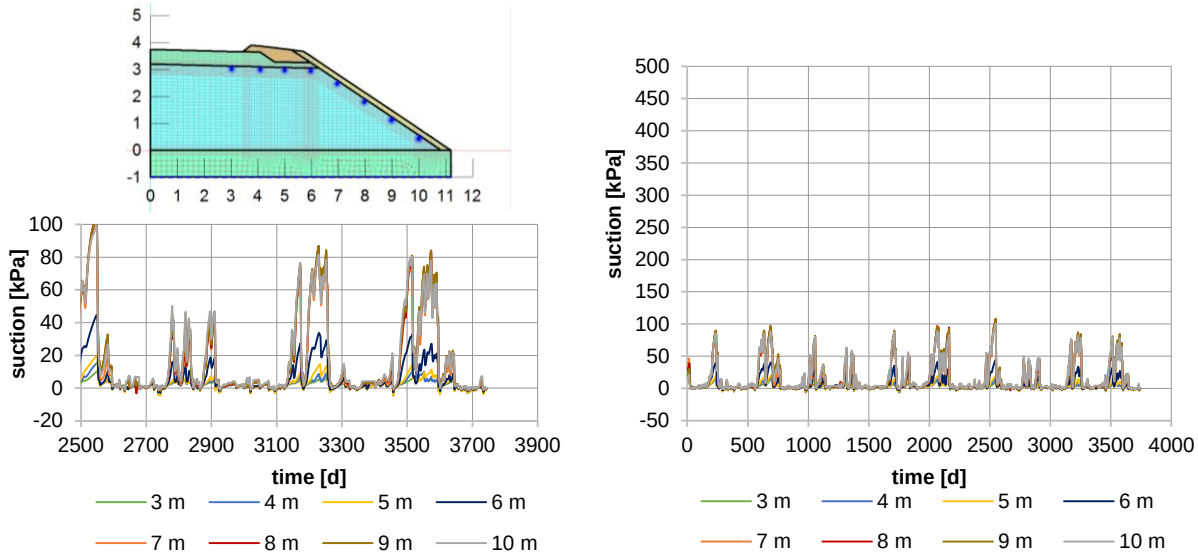


Figure 12. *Changes of suction with time at different positions at the upper part of the core for basic model 2 with organic clay (OT)*

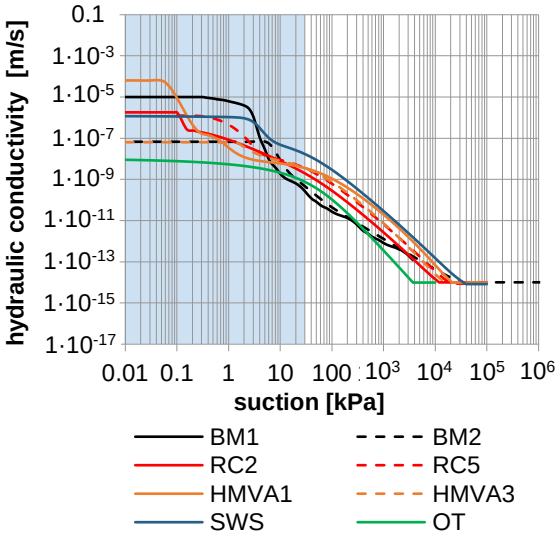


Figure 13. *Range of suctions during wetting periods (blue area) at the upper part of the core for basic model 2*

3.3 Comparison of basic model 1 and basic model 2

In order to evaluate the contribution of the drainage layer in the water balance of embankments the results of basic model 1 and basic model 2 were compared. According to the simulations, the usage of a drainage layer can lead to a significant reduction of the core outflow in the range of 10.5 % (SWS) to 30.6 % (BM1) of the total amount of precipitation. Figure 14 shows the absolute reduction of the core outflow for the different materials, defined as the difference of core seepage between the two basic models divided by the core seepage of basic model 2. Due to the drainage layer the core outflow was reduced by at least 30 %. Except for the simulation with SWS, an absolute reduction between 70 % and 88 % was computed. The results are in agreement with the laboratory results reported by Kellermann-Kinner et al. (2016, 2017).

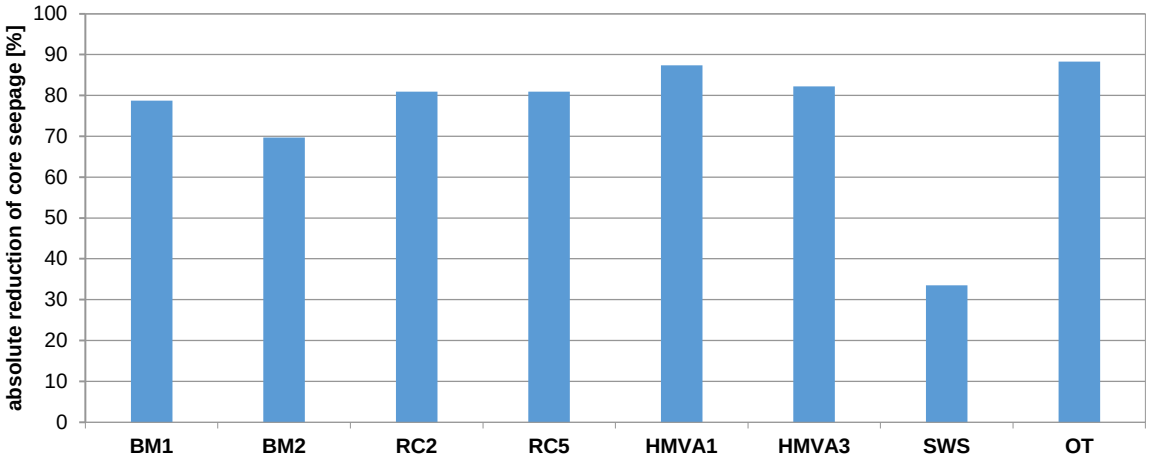


Figure 13. *Absolute reduction of core seepage due to the drainage layer for the different core materials*

4 CONCLUSIONS

The following conclusions can be derived from the simulations:

- The amount of seepage from the core of the embankments without drainage layer ranges between 29 % to 39 % of the total precipitation, when the saturated permeability of the core material is higher than $1 \cdot 10^{-8}$ m/s. A significant decrease in the amount of seepage is observed only when the saturated permeability is lower than $1 \cdot 10^{-8}$ m/s. Moreover, for the materials with a permeability coefficient higher than $1 \cdot 10^{-8}$ m/s the amount of seepage is not directly dependent on the saturated hydraulic conductivity of the core.
- Applying a drainage layer above the core leads to a significant reduction of the core seepage of at least 30 %. Except for the model with steelwork slag, the calculated core outflow for the materials with $k_{sat} > 1 \cdot 10^{-8}$ m/s is between 3.6 % and 10.8 % of the precipitation. In the case of steel slag (SWS) a much higher core outflow of 20.8 % of the precipitation has been computed. The calculation with the organic clay (OT) as core material ($k_{sat} = 1 \cdot 10^{-8}$ m/s) resulted in a very low core outflow of 1.4 %.
- The calculation results obtained on the models with drainage layer demonstrate that the saturated hydraulic conductivity of the core material for the predominantly permeable materials considered here is not a suitable indicator for predicting the amount of core seepage. As the saturated permeability coefficient of the core material increases, the amount of seepage water from the core does not increase respectively. This can be clearly seen by the calculation with HMVA1. Although this ash has the highest saturated permeability of all investigated core materials ($k_{sat} = 6.4 \cdot 10^{-5}$ m/s), the determined core outflow of 3.6 % is very low. The effectiveness of the drainage layer and the resulting core outflow are strongly influenced by the hydraulic conductivity of the core material in the unsaturated state. In particular the hydraulic conductivity corresponding to the soil suction in the core at the upper boundary to the drainage layer is of importance.
- Due to the very low saturated permeability coefficient of the organic clay OT (less than $1 \cdot 10^{-8}$ m/s according to the requirements of MTSE) the computed amount of seepage is for this material, as expected, very low. Thus, it confirms the suitability of construction method E according to MTSE for minimizing the quantity of seepage water from building materials and contaminated soils.

5 ACKNOWLEDGEMENTS

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