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Calibration of a simple 1D model for the hydraulic response of regional dykes in the Netherlands

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Abstract. A simple numerical model was set up to investigate the hydraulic behaviour of a regional dyke to improve understanding of the response under variable atmospheric conditions. The unsaturated hydraulic properties of the dyke body and the relevant foundation layers were calibrated either on the results of laboratory tests or on a national database, namely the Staringreeks, compiled for typical Dutch soils. The boundary conditions were imposed according to the weather history at the top, and to the pore pressures measured in the field at the bottom of the representative soil column. The results indicate that a simple 1D model is able to accurately reproduce the suction time history in the dyke core, provided the hydraulic conductivity and soil water retention properties are properly calibrated. The optimised hydraulic conductivities are typically two orders of magnitude higher than the saturated hydraulic conductivity from the laboratory tests, but comparable to the ones suggested in the database developed on field data. The work highlights that cautious evaluation of laboratory data is needed for field applications, and that direct information from the field should be used to validate numerical models in the presence of organic soils.

1 Introduction

In 2003, a regional dyke in the city of Wilnis, consisting primarily of peat failed under dry conditions [1]. The extreme drought played an important role in the failure of the dyke. This disaster led to the initiation of several research programmes, aimed at better understanding the hydraulic response of regional dykes. Yet, the effects of climatic stresses on regional dykes are not well understood. In addition, the unsaturated hydraulic response of the materials used for the construction of Dutch dykes has not been studied extensively. While extreme weather events become more frequent, better understanding of the hydraulic behaviour of these regional dykes is required. The goal of this work is to facilitate the development of more reliable hydro-mechanical models for regional dykes.

This study proposes a 1D numerical model to simulate the hydraulic response in the dyke. In the model, the unsaturated flow is described by calibrating a simple water retention model and the saturated hydraulic conductivity. The dependence of hydraulic conductivity on the degree of saturation is evaluated through a simple analytical literature model. At the upper boundary of the representative column, a time dependent water influx is obtained from actual weather data, and the lower boundary condition is imposed from pore pressure measurements in the field. Starting from the initial condition, the time history of pore pressures throughout the soil profile is calculated.

The model is assessed with the available field data from a regional dyke in the Leendert de Boerspolder. The standpipe measurements inside the dyke layer and peat layer are used to evaluate the accuracy of the numerical model in predicting the pore pressures history.

2 1D numerical model

2.1. Model description

A simple numerical model was developed to solve the head-based Richards equation [2] for time dependent boundary conditions using a finite difference discretisation:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\cdot\left[K(h)\cdot(\frac{\partial h}{\partial z}+1)\right] \tag{1}$$

where C is the specific moisture capacity.

The following assumptions were made:

(1) Incompressible pore-water;
(2) Rigid soil skeleton;
(3) Pore air connected to the atmosphere (constant air pressure);
(4) Individually homogeneous soil layers;
(5) The effects of hysteresis in soil-water retention response were disregarded.

The soil water retention curve was described by a simple van Genuchten curve [3]:

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$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} \tag{2}$$

where θ is the volumetric water content, θ_s is the saturated volumetric water content and θ_r is the residual volumetric water content, α and n are fitting parameters and $m = (n - 1) / n$. The hydraulic conductivity, K, is defined according to Mualem [4]:

$$K(\theta) = k_s \cdot S_e^{1/2} [1 - (1 - S_e^{1/m})^m]^2 \tag{3}$$

with

$$S_e = \frac{1}{[1 + |\alpha h|^n]^m} \tag{4}$$

where k_s is the saturated hydraulic conductivity.

Fig. 1 shows the 1D model set up to simulate the hydraulic response in a two-layers unsaturated porous medium. The boundary conditions are given by an upper influx, q_{upper} (t), and a lower boundary pressure head, h_{lower} (t).

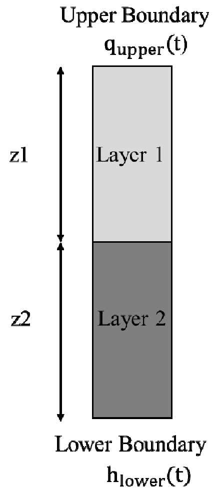

Fig. 1. 1D numerical model for hydraulic response.

2.2 Model validation

The model was validated with the results published by Wu et al. [5]. The initial pressure head throughout the whole column is -2m. The thicknesses of the upper and lower layers are 0.5 m and 1.5 m, respectively. On the upper boundary an influx q_{upper}(t) = 3 mm/d is imposed, while a constant pressure head h_{lower}(t) = - 2m is imposed at the bottom. Table 1 shows the Van Genuchten (VG) parameters and saturated hydraulic conductivity of the soil layers [6]. Fig. 2 presents the calculated pressure head profile, which accurately replicates the results by Wu et al. [5].

Table 1. VG parameters and saturated hydraulic conductivity of the soil layers

Layer	θ_r [-]	θ_s [-]	α [m^{-1}]	n [-]	k_s [m/s]
1	0.08	0.51	1.05	1.547	3.21×10^{-6}
2	0.14	0.50	0.86	1.611	8.42×10^{-7}

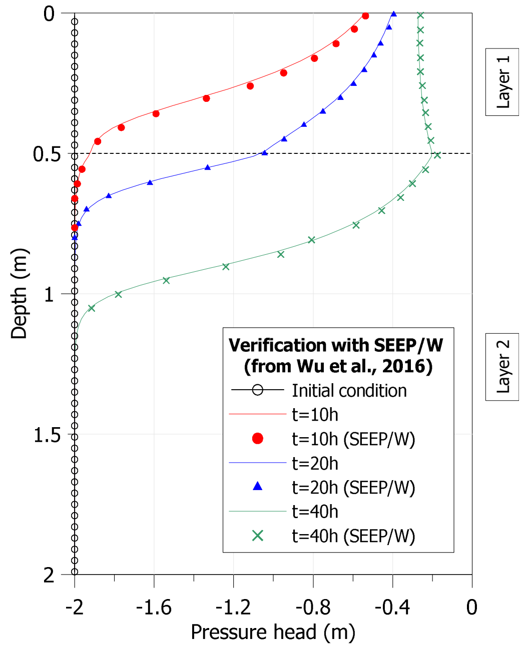

Fig. 2. Calculated pressure head profile and results from Wu et al. (2016).

3 Leendert de Boerspolder

The model was used to analyse some field observation on a regional dyke located at the Leendert de Boerspolder in the western parts of the Netherlands, which had been offered for a prototype stress test by the Waterboard HH Rijnland and STOWA, the foundation for research on regional dykes in the Netherlands. The dyke was monitored during one year under normal work conditions, including standpipe measurements. The pore water pressures were recorded at four different depths, as shown in Fig. 3 ([7]). In this study, the measurements from January to May 2015 were used.

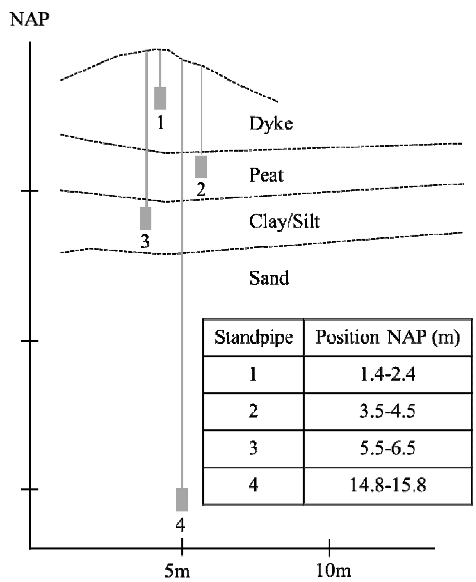

Fig. 3. Setup of the standpipe measurements at the Leendert de Boerspolder.

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3.1. Geometry and 1D approximation of the dyke

In order to model the hydraulic response of the dyke, a 1D approximation of the field conditions was made. According to the boreholes profile, where the standpipes were installed, the upper two soil layers, the dyke body and the underlying peat layer were mostly affected by the weather stresses, while in the lower layers the hydraulic head kept almost constant and regulated by the canal and the inner polder water levels.

The initial condition was assigned based on the pore pressure measured at the beginning of the simulated time history. Fig. 4 provides an overview of the initial conditions in the 1D approximation of the dyke.

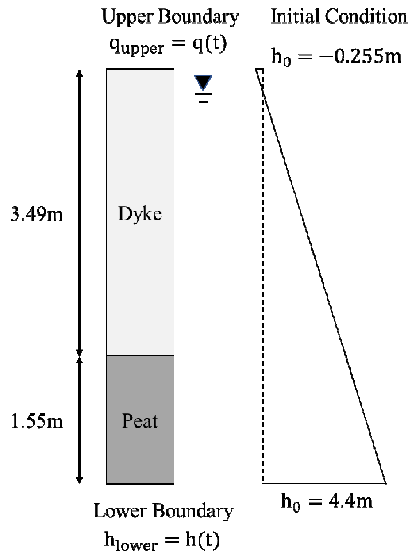

Fig. 4. An overview of the initial conditions in the 1D approximation of the dyke.

3.2. Boundary conditions

To assign the net flux of water at the upper boundary, data from the nearest weather stations to the site were used. The average reference crop evapotranspiration data at Valkenburg and Schiphol were combined with rainfall data at the station of Roelofarendsveen. The daily net positive outflux of water at the ground level was obtained by subtracting the rainfall from the evapotranspiration rate (Fig. 5). In the model a run-off condition was activated whenever positive pressure was detected at the ground level. At the lower boundary, the pore pressure head measured in the silty clay layer was imposed, assuming constant head in the layer (Fig. 6).

3.3. Material parameters

The van Genuchten (VG) parameters and saturated hydraulic conductivity of the dyke and peat layer were assigned either from the data base Staringreeks on Dutch soils by Alterra [8] or from the results of laboratory tests [9].

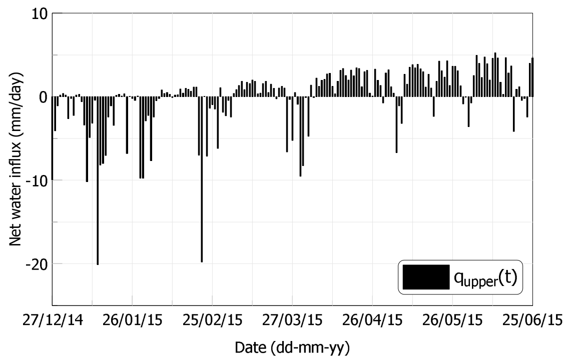

Fig. 5. Simulated total net out flux at the upper boundary.

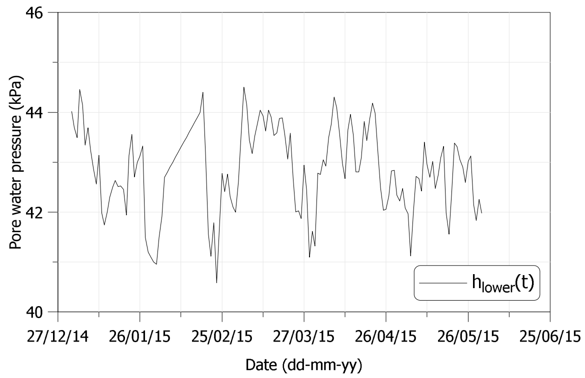

Fig. 6. Pressure head at the lower boundary, $h_{lower}(t)$.

The data base compiled by Alterra collects VG parameters and saturated hydraulic conductivity of the 36 most typical Dutch soils, based on their grain size distribution, and includes common Dutch peats. Table 2 shows the parameters chosen for the dyke body and the peat layer from the report information. The dyke material had been also studied in the laboratory, with a combination of Hyprop and Dew Point data, and the corresponding VG parameters are given in Table 3. It is worth noting that the two sets of estimated parameters mostly differ for the steepness of the water retention curve and for the dramatic change in the order of magnitude of the hydraulic conductivity.

Table 2. VG parameters and saturated hydraulic conductivity of the dyke and peat layers suggested by the Staringreeks.

Layer	θ_r [-]	θ_s [-]	α [m^{-1}]	n [-]	k_s [m/s]
Dyke	0.06	0.46	0.35	2.37	1.78×10^{-6}
Peat	0.00	0.89	0.06	1.44	1.24×10^{-7}

Table 3. VG parameters and saturated hydraulic conductivity of the dyke layer from laboratory data.

Layer	θ_r [-]	θ_s [-]	α [m^{-1}]	n [-]	k_s [m/s]
Dyke	0.0	0.42	0.31	1.33	2.00×10^{-8}

4 Analysis of the results

4.1. Staringreeks parameters

The calculated and measured pore pressures in the dyke and the peat layer are shown in Fig. 7 and Fig. 8, respectively. The numerical results underestimate the measured pore pressures in both layers, compared to the field results. Besides underestimating the pore pressures, this parameters combination gives a trend over time which does not match with the true response of the system to the climatic history.

4.2 Laboratory parameters

The VG parameters and saturated hydraulic conductivity for the dyke material were investigated on homogenous samples in the laboratory [9]. The corresponding parameters are given in Table 3. For the peat layers, the same parameters as before where adopted in the absence of specific information. The comparison between measures and calculated pore pressures in Fig. 9 and Fig. 10 show that this combination allows better reproducing the trend of pore pressures in the peat layer. However, the limited hydraulic conductivity of the dyke body makes it quite insensitive to the external condition and limits the calculated recharge, with substantial decrease of pore pressures over time.

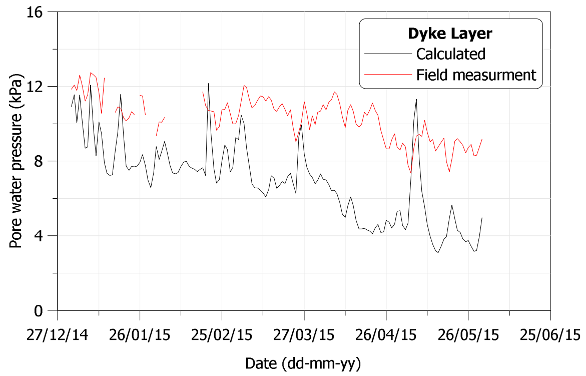

Fig. 7. Calculated and measured pore pressures in dyke layer (Staringreeks parameters, Table 2).

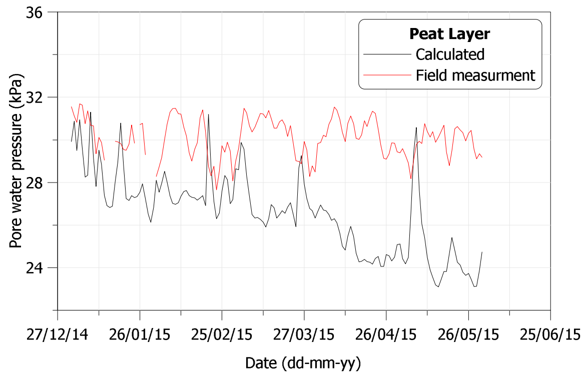

Fig. 8. Calculated and measured pore pressures in peat layer (Staringreeks parameters, Table 2).

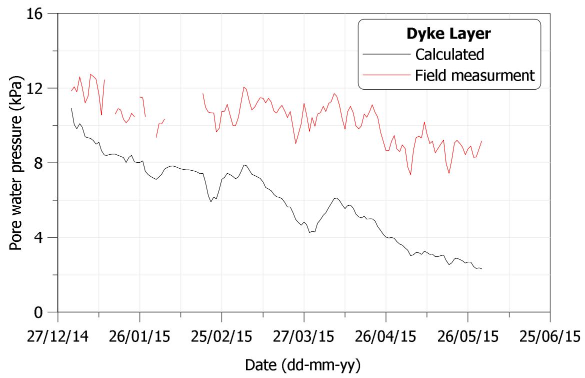

Fig. 9. Calculated and measured pore pressures in dyke layer (Laboratory parameters for the dyke layer, Table 3).

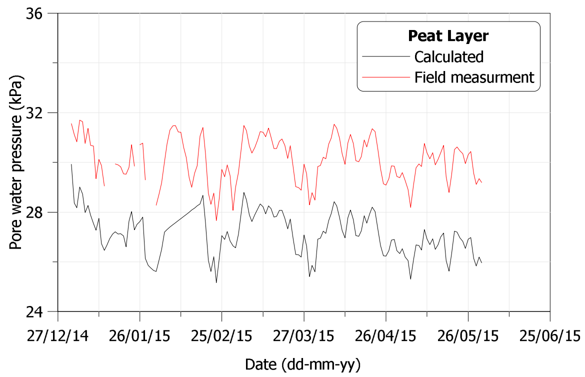

Fig. 10. Calculated and measured pore pressures in peat layer (Laboratory parameters for the dyke layer, Table 3).

4.3 Parameters optimisation

The results in the previous section suggest that neither the laboratory information nor existing database, mainly derived for agronomy applications, can reproduce accurately the response of a dyke in the field at increasing climatic stresses than those experienced historically.

This lack of representativeness is believed to come from possible changes in the fabric of the compacted soil in the field. Lumps formation was observed over very dry periods, which is responsible for the formation of macro-voids, affecting the global hydraulic response. Amoozegar & Warrick [10] pointed out that the presence of macro-voids in the field allows for a higher hydraulic conductivity than that characterising intact samples of the material tested in the laboratory. The uncertainty is propagated to the water retention properties to be used in the analysis of the field response.

A sensitivity analysis was performed on the soil-water retention properties and saturated hydraulic conductivity of the two layers, to optimise the calibration of the parameters directly on the field observations. The results in Fig. 11 and Fig. 12 show that the calculated response in the dyke layer is rather insensitive to the hydraulic conductivity of the underlying peat layer, at least in the investigated range. The dominant properties on the response of the system are the hydraulic conductivity of the dyke body and, to a lesser extent, the water retention properties of the lower peat layer, as shown by the results presented in Fig. 13 and Fig. 14 obtained with an optimised parameters combination.

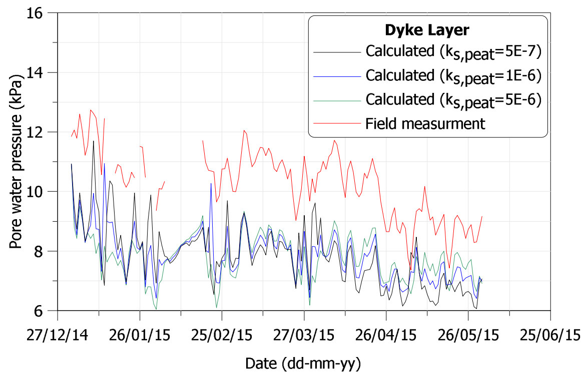

Fig. 11. Sensitivity analysis on the hydraulic conductivity of the peat layer.

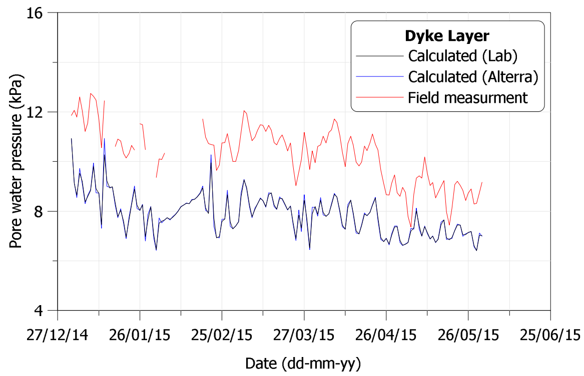

Fig. 12. Sensitivity analysis on the soil-water retention properties of the dyke layer.

Table 4. Optimized VG parameters and saturated hydraulic conductivity of the dyke and peat layer.

Layer	θ_r [-]	θ_s [-]	α [m^{-1}]	n [-]	k_s [m/s]
Dyke	0.06	0.46	0.348	2.372	5×10^{-6}
Peat	0.00	0.89	0.063	1.435	1×10^{-6}

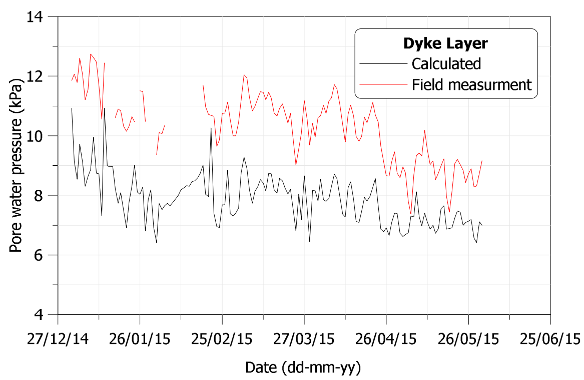

Fig. 13. Calculated and measured pore pressures in dyke layer (Optimised parameters).

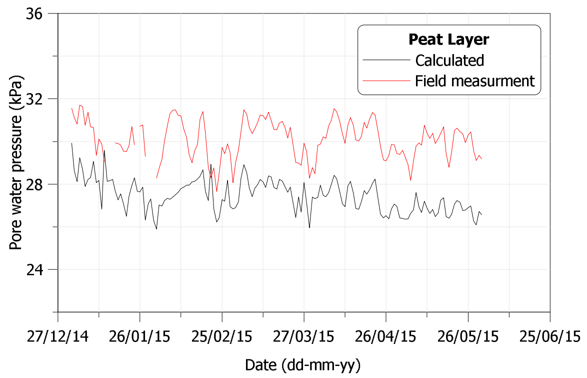

Fig. 14. Calculated and measured pore pressures in peat layer (Optimised parameters).

The numerical results from the simulations run with the optimised parameters in Table 4 well capture the trend of the hydraulic response in the field. However, a systematic shift is observed between the calculated and the measured pore water pressures. The discrepancy is due to the uncertainty on the exact depth of the water pressure sensors, which were installed in a 1 m thick filter in each layer. The uncertainty in the sensors position affects the absolute value of the reference pore pressure, but not how it changes over time.

In order to eliminate this uncertainty in the validation of the model, the comparison between the calculated and the measured pore pressure changes over time is reported in Fig. 15 and Fig. 16.

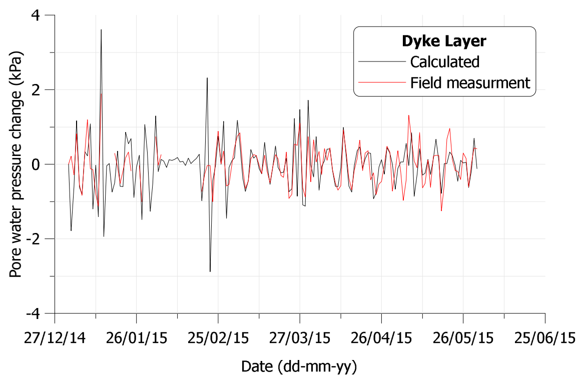

Fig. 15. Calculated and measured pore pressures change in the dyke layer.

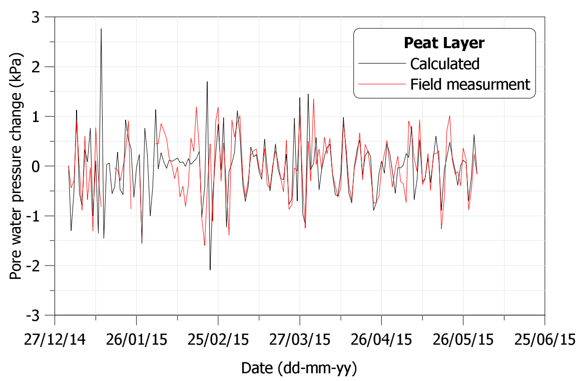

Fig. 16. Calculated and measured pore pressures change in the peat layer.

5 Discussion and conclusions

The results of the numerical study show that a priori information, either from laboratory data or from information at the regional scale, fail in accurately reproducing the response of typical dyke materials in the field, when simplified models are adopted to assess the response of the system to the climatic history. This lack in accuracy may come from different contributing factors at different scales, which were disregarded in the simplified approach.

At the material scale, the assumption of a rigid soil skeleton disregards that swelling and shrinkage will affect the hydraulic response of the soil, depending on the season. It is unlikely that a model which disregards hydro-mechanical coupling can be calibrated to be equally accurate over an entire year. Over the last one and a half month, the model accuracy on the dyke body response reduces, correspondingly to a decrease in rainfall and an increase in the net evapo-transpiration. Drying in the field tends to create big lumps of soil, leaving interconnected macro-voids. These increase the hydraulic conductivity and decrease the water storage capacity in the field compared to those observed on intact specimens tested in the laboratory. The scale effect was dramatic on the specific dyke investigated, but is believed to be relevant in the majority of the cases.

At the field scale, the spatial variability of the response of the dyke body will be affect the response, besides the heterogeneity of the intact soil [11, 12]. Also, some limitation in the calculated response comes from the uncertainty on actual weather conditions at the site. The upper boundary condition was approximated by data coming from nearby weather stations. However, precipitation events can be localised and can be significantly different from the assumed ones. In addition, the dyke vegetation cover in the field may respond differently from the reference crop behaviour assumed in the analysis.

Notwithstanding the previous limitations, the model was able to describe the hydraulic response of the regional dyke in the Leendert de Boerspolder with sufficient engineering accuracy, when calibrated by back analysis of field data. Best fitting soil-water retention properties and saturated hydraulic conductivity from field data was essential to reliably predicting the system response over a long time period.

Eventually, it is worthwhile remarking that the physical processes, especially cracking, affecting the response of the system over drying may also affect the reliability of the field measurements. Overall, even if laboratory data have to be evaluated carefully, they cannot be substituted by field measurements alone, because the latter cannot be validated in the absence of any information on the material. The results of this case history tend to suggest that including fabric features and cracks on representative physical model samples in the laboratory, increasing the scale of investigation, would help in a more reliable calibration of numerical models to be used in the engineering practice.

Acknowledgments

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