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DOI
10.53243/NUMGE2023-444

Publication date
2023

Document Version
Final published version

Published in
Proceedings 10th NUMGE 2023

Citation (APA)
Vardon, P. J., Aguilar Lopez, J. P., & Dieudonné, A. A. M. (2023). The soil-atmosphere interface: an important boundary condition or an unnecessary complicating factor? In L. Zdravkovic, S. Kontoe, D. M. G. Taborda, & A. Tsiampousi (Eds.), *Proceedings 10th NUMGE 2023: 10th European Conference on Numerical Methods in Geotechnical Engineering* Article 444 International Society for Soil Mechanics and Geotechnical Engineering. https://doi.org/10.53243/NUMGE2023-444

Proceedings 10th NUMGE 2023
10th European Conference on Numerical Methods in Geotechnical Engineering
Zdravkovic L, Kontoe S, Taborda DMG, Tsiampousi A (eds)

https://doi.org/10.53243/NUMGE2023-444

The soil-atmosphere interface: an important boundary condition or an unnecessary complicating factor?

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ABSTRACT: Soil-atmosphere interaction occurs frequently in most geotechnical situations. By including it in analyses, a high computational load can occur, and analyses are made more complex. This paper explores the key processes and demonstrates the impact and advantages of quantifying soil-atmosphere interactions. Possibilities of utilising the soil atmosphere interaction to accelerate soil processes and reduce environmental impact, and to generate energy are shown, highlighting benefits of considering soil-atmosphere processes. It is also seen that it is not always necessary to directly include the processes in analyses, but that consideration of the processes can lead to approaches to directly monitor or guide monitoring. The soil-atmosphere interface is important, and whether it is necessary, useful or damaging to consider in analyses is situation dependent.

Keywords: Soil-atmosphere; cracking

1 INTRODUCTION

Geotechnical structures, such as dykes and embankments, are pervasive in civil engineering due to their ability to alter topology in a cost effective way, and are therefore a fundamental part of critical infrastructure. In addition, natural slopes are often found or are altered close to critical infrastructure. The stability of both is a key question for society. The cost of failures is usually significantly more than of maintenance, especially in the case of major landslides or flooding. However, due to the pervasive nature of such structures and natural slopes, costs for assessment and maintenance are significant for many countries. Due to the long history of using geotechnical structures, there is a significant presence of ageing geotechnical structures, and those which were not constructed to modern standards.

In typical geotechnical stability analyses, the soil is usually modelled as a continuum which finishes at the soil-atmosphere boundary. There is typically no account taken of any processes which occur at this location, other than external mechanical loading. However, it is a highly dynamic interface. The weather conditions, e.g. solar radiation and precipitation, are applied to the boundary, and frequently the interface layer hosts vegetation, which itself impacts the effect that weather conditions have on the soil. Moreover, with climate change increasing sea-levels and resulting in more extreme weather events, the loads which climatic processes apply to geotechnical structures may at least temporarily increase. The inclusion of these processes would require numerical models which are Multiphysics and temporal in nature, vastly increasing computation demand, while geotechnical practice has successfully used models in design which do not include these processes for many decades.

This paper attempts to answer the question of whether the soil-atmosphere interface is important to characterise, or whether it simply makes design calculations difficult.

2 SOIL-ATMOSPHERE PROCESSES

Soil reacts to coupled thermo-hydro-chemo-mechanical processes and soil properties may themselves also be properties of the current or past thermo-hydro-chemo-mechanical state (e.g. Gens, 2010; Kolditz et al., 2012). Depending on the characteristics of any problem which is being analysed, the relative dependence of each of the processes, the couplings or material property dependence differs.

The stability of geotechnical structures impacted by soil-atmospheric processes was reviewed by Vardon (2015) and Elia et al. (2017), with the paper of Vardon focusing on the impacts of climate change on geotechnical infrastructure and the paper of Elia et al. focusing on numerical modelling of slope stability-vegetation-atmosphere interaction. Kandalia et al. (2023) provided an updated overview, extending the topics from the two aforementioned papers to include impacts of thawing of permafrost areas and acidification, and methods for the quantification of local climate scenarios from global models, i.e. downscaling.

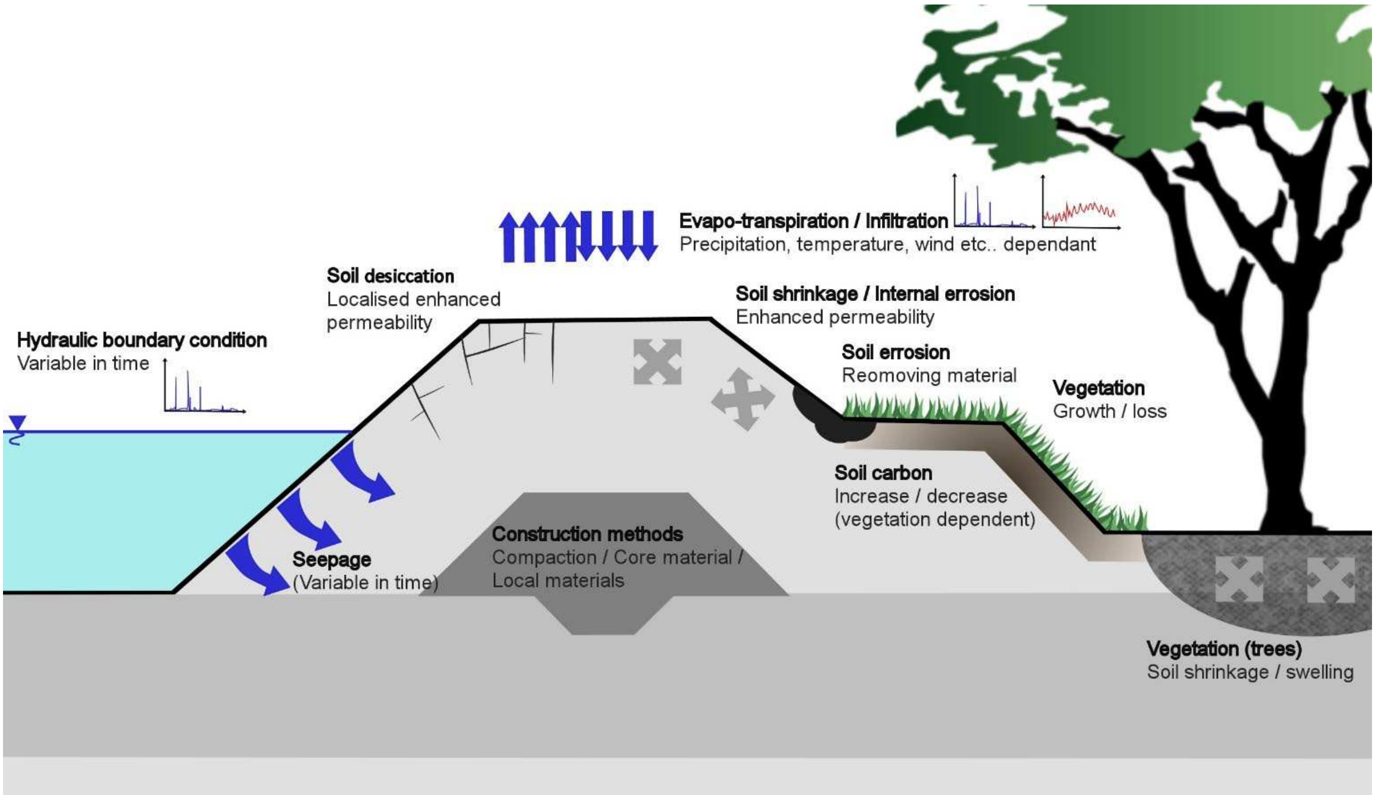

Figure 1. Soil-atmosphere interaction (after Vardon, 2015)

A schematic of several key soil-atmosphere conditions and their influence was produced by Vardon (2015) and is shown in Figure 1. In this figure, it is seen that there are thermo-hydro-mechanical processes directly driven by the boundary conditions, and several which are indirectly impacted via changing properties.

The key soil-atmosphere thermo-hydro-mechanical boundary conditions are:

(i) a heat flux, which is controlled partly by the external temperature, partly by the radiation, and partly by the temperature of the soil close to the boundary. When radiation is not applied (e.g. during the night or if the structure is shaded), a fixed temperature boundary conditions may be appropriate to be applied in models. Additional thermal energy is transferred into or out of the soil via water movement, either due to evaporation or advective flow;

(ii) a water flux, which is driven at the soil-atmosphere boundary by evapotranspiration and precipitation, but is impacted by the state of the soil, which can, for example, cause water run-off, and where the structure is immediately adjacent to free water, an external pore pressure is applied;

(iii) external mechanical loads.

In the cases of water and heat flux, the state of the soil, the weather conditions and possible vegetation cover impact the rate of the water or energy transfer.

Weather conditions, including the wind speed, water vapour pressure or humidity, heat supply and temperature define the maximum evaporation. The soil state, i.e. the degree of saturation, the specific volume and the temperature, and its properties, including permeability and thermal conductivity, strongly impact the fluxes. The water boundary flux can be limited either from the soil or from the local weather conditions.

Vegetation, which can be present on the surface of many geotechnical structures plays an important role, and evolves with time, weather conditions and maintenance. The type of vegetation, and specifically the root type, is also important. Vegetation plays several roles (Schapendonk et al., 1998). It can intercept precipitation and it can transpire water which then evaporates. The relative importance of each of these two processes depends on the vegetation type, but also the vegetation health and maintenance (e.g. cutting or mowing). The vegetation will continuously grow and die, and this is directly impacted by the weather and the soil state, and in turn impacts the soil state. The vegetation, in response to climatic conditions, has an annual cycle due to water and energy availability. Vegetation can strengthen the soil and can impact the permeability of the soil (e.g. Toll et al., 2019). Strength from vegetation can also provide resistance to erosion. The root depth of the vegetation also affects whether it is reasonable to consider the impact of vegetation as a boundary condition, or whether another approach would be preferable.

Soils may desaturate and/or deform in response to evaporative water flux. Surface drying and wetting may follow complex and non-unique water content–suction paths, which can also differ significantly between different soil layers in the near surface (Bordoni et al., 2021). Such evaporative fluxes can cause surface cracking (Bordoni et al., 2021; Cui, 2022). This will have an impact on the strength and the permeability of the boundary layer. In some cases, cracks are able to seal (where hydraulically they are closed, but mechanically have different properties) or heal (where both hydraulically and mechanically their properties recover) (e.g. El-Zein et al., 2021; Tian et al., 2023). However, both sealing and healing are not yet well understood.

Heavy rainfall is well-known to trigger landslides, for example due to loss of suction, and possible liquefaction landslides (e.g. Di Carluccio, 2023), with the rate and the quantity of rainfall both important.

The timeframe of when analyses are valid is important. As discussed by Vardon (2015), Elia et al. (2017) and Kandalia et al. (2023) the climate is changing and this will impact the initial and forcing conditions. Costa et al. (2023) investigated this impact by simulating how weather patterns from 1990-2080 could impact the moisture and temperature of the shallow subsurface, finding in particular that the vadose zone increased over time.

The temperature of geotechnical infrastructure exposed to atmospheric conditions will change, but within relatively limited bounds. Freezing may influence the soil structure, but the infrastructure will also contain considerable thermal energy and limit the frozen depth. Elevated temperatures, except at the very surface, are likely to remain with ±5°C with respect of the average (e.g. Cleall et al., 2015), and are therefore unlikely to substantially change the mechanical properties (see Golchin et al. (2022) for a compilation of thermal effects on soils). The temperature, as mentioned previously, does significantly affect the potential evaporation and the vegetation growth/death rates.

As with most geotechnical problems, the specific type and objective of the infrastructure, the geometry and the local soil conditions impact the performance. However, considering soil-atmosphere interactions means that further aspects of the soil state, the weather and weather history and the possible vegetation cover are also important. For example, dykes and embankments have a large surface area in comparison to their soil volume and are frequently vegetation covered. This implies that they are susceptible to soil-atmosphere processes. Two contrasting impacts occur: (i) the soil gets heavier with an increasing water content and therefore the shear stresses increase, and (ii) the shear strength is affected by several processes. One process is the increase in shear strength with soil suction, another is the potential decrease in strength due to cracking. The cracking then goes on to impact the permeability. The temperature plays a role in determining the soil-atmosphere processes and does not have a large direct impact on the process. Energy geostructures however, extract or inject thermal energy into the ground. Often this is done on a seasonal basis, where the energy is stored for several months. The soil-atmosphere thermal interaction is then a major influence, and depending on the depth of the structure can substantially reduce the efficiency of the storage.

3 IMPACT OF VEGETATION ON STABILITY

One of the main, and often critical, failure mechanisms of geotechnical structures is macro-stability failure. Macro-stability refers to the global shear failure of the structure and underlying foundation. An approach to dynamically simulate the impact of vegetation on the macro-stability of dykes was made by Jamalinia et al. (2019). In this work, a crop model (LINGRA) (Schapendonk et al., 1998) was used to simulate grass growth/death and changes in the water content of a surface soil layer. A simple 1D mass balance approach is taken, whereby changes in water content (w) are determined by the precipitation (P) minus the interception (I), the evapotranspiration (ET), the drainage (D) and the run-off (R), i.e.

$$\Delta w = P - I - ET - D - R \tag{1}$$

Each of these aspects is calculated based on the current state of the boundary soil layer, the vegetation and an input weather data series. The state of the vegetation is included via a variable called Leaf Area Index (LAI), which is updated in each time step by calculating the growth and death rates, which are functions of the soil state (water availability) and the weather (precipitation, solar radiation and temperature). Maintenance, such as mowing, can be included which sets the LAI to the desired value. The crop model is run prior to analysis of stability, and results in time series of LAI, water flux into the soil, drainage through the surface soil layer and the water content of the surface soil layer. In this approach, the surface soil layer is determined as the rooting depth of the vegetation.

A commercial soil stability software (Plaxis) was then used to simulate the stability of an example dyke. Plaxis was used in two analysis steps: (i) hydraulic material properties were calibrated based on the calculated drainage from the surface layer and water flux into the soil – a new set of calibrated parameters were calculated

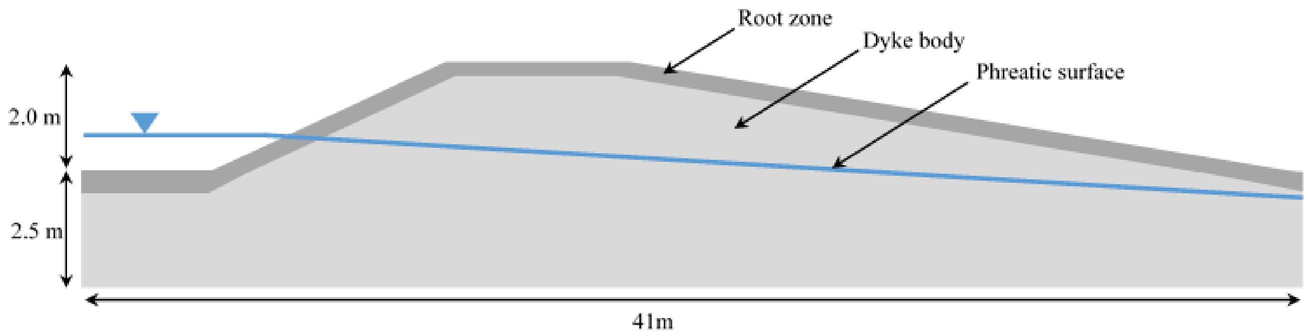

Figure 2. Example dyke model domain

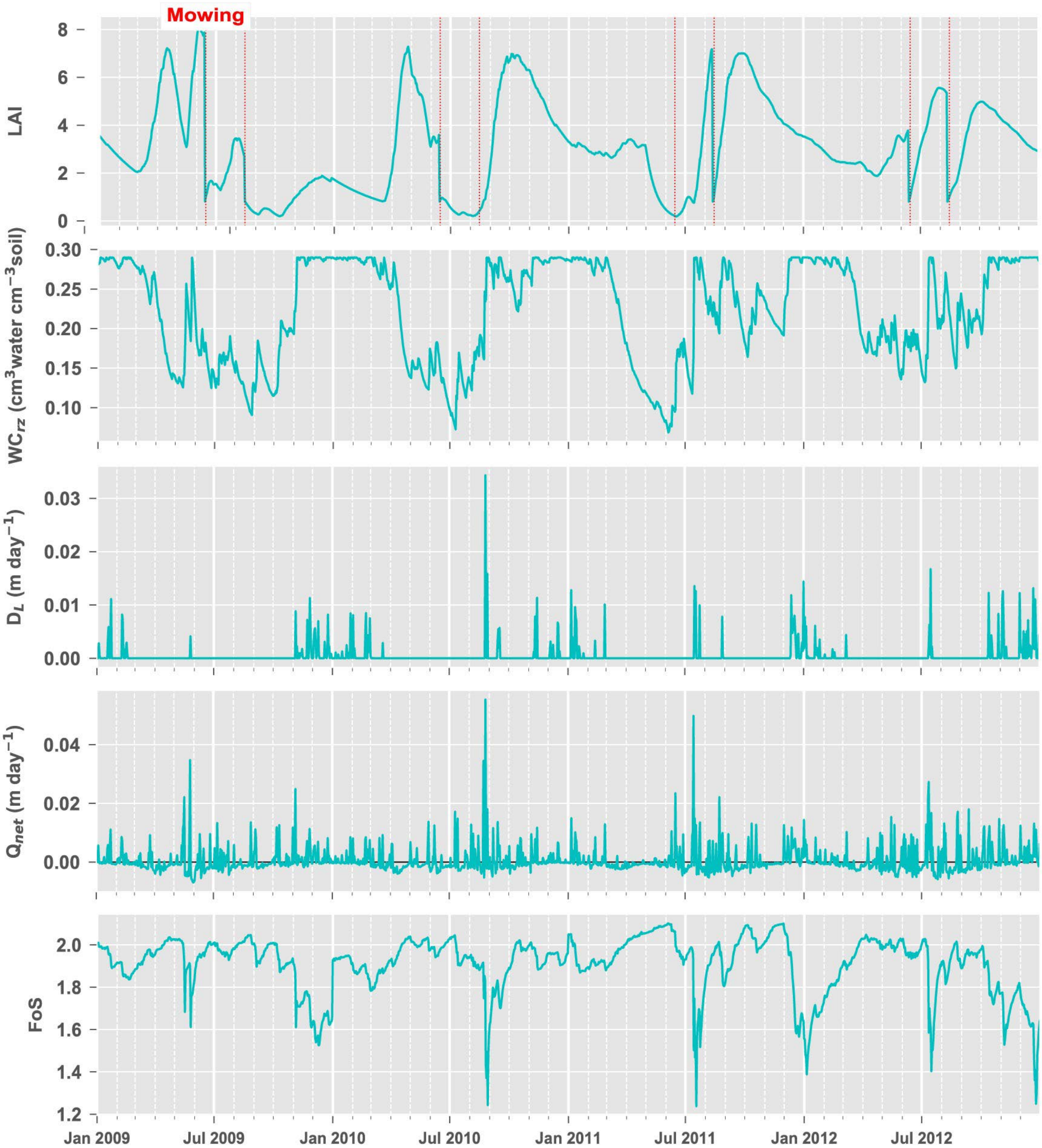

Figure 3. Model output. LAI, Root zone water content (WC_{rz}), Drainage (D_L) and water flux into the soil (Q_{net}) are output from the crop model and the Factor of Safety (FoS) is output from the calibrated stability analysis (after Jamalinia et al., 2019).

regularly throughout the time series. The model domain was 1D and of the same dimensions as the crop model; (ii) a hydro-mechanical analysis, which incorporated unsaturated flow and the impact of suction on strength, and was setup to produce a time series of pore water pressure and displacement throughout the calculation domain, and a time series of factor of safety. The domain was set up as a 2D dyke (shown in Figure 2), where the root zone was 40cm and the water flux calculated from the crop model was applied equally across the dyke surface – this means that there was no consideration of spatial variability of the flux, including for example differences in run-off.

The properties of the dyke and the weather conditions are taken from the Netherlands, which means that precipitation occurs all year round, with moderate peaks late summer (e.g. August) and both radiation and temperature are the highest in mid-summer (July) and lowest mid-winter (January).

Figure 3 shows a selection of the results. LAI largely grows in spring where increased radiation encourages growth, except in dry years (illustrated by the water content reducing). In wet summers, the vegetation continues to grow, yet dies off in dry summers. In mid-winter, when there is usually sufficient water, the vegetation does not grow due to grow being limited by the amount of solar radiation and low temperatures. This intuitive result gives confidence in the model performance. Drainage is high during high levels of precipitation, but only when the soil is sufficiently wet. Hydraulic conductivity reduces when soil is unsaturated, and rainfall in dry periods does not result in significant drainage. The Factor of Safety (FoS) reacts closely to the drainage, decreasing sharply when there are single large or multiple closely spaced smaller drainage events. These often happen when LAI is low (as interception of rain is low), but after periods when there is a positive water flux to ensure that the surface is permeable and the vegetation has not had time to grow. This often occurs if there is a reasonably wet autumn period followed by a large single precipitation event.

It should be noted that vegetation cover also impacts other possible failure mechanisms, such as erosion, but this has not been considered here.

4 IMPACT OF CRACKING ON STABILITY

The work of Jamalinia et al. (2019) was updated in Jamalinia et al. (2020) to include an approach for the impact of surface cracking. Surface cracking is a discrete phenomenon, which is challenging to include in numerical analyses due to mesh size, continuum assumptions and the physics of soil cracking only being unravelled in research at present (e.g. Tollenaar et al., 2017). Therefore, a set of continuum assumptions was made in order to incorporate the impact of cracking.

Cracks were assumed to be vertical in the root zone and limited in depth to the root zone. In the crop model used to establish the water flux and drainage into deeper soil layers, the fraction of the surface area of the dyke that is cracked was introduced as a variable (A_{crack}). This was calculated from the using a shrinkage curve and another parameter which controlled how much of the shrinkage resulted in subsidence and how much in lateral shrinkage (r_s). The surface area fraction that is cracked (A_{crack}) is equal to the volume fraction of the root zone which is cracked (V_{crack}) assuming that all cracks are vertical, and can be related, via simple volumetric considerations to the total volume of the soil which has shrunk (V_{shrink}) and the portion which is vertical ($V_{subsidence}$), as:

$$\Delta A_{crack} = \Delta V_{crack} = \frac{\Delta V_{shrink} - \Delta V_{subsidence}}{1 - \Delta V_{subsidence}} \quad (2)$$

and

$$V_{subsidence} = 1 - (1 - V_{shrink})^{(1/r_s)} \quad (3)$$

Parameter r_s changes from 1 for situations where only subsidence occurs (very soft soils) to >3 where cracking behaviour dominates.

The cracks were assumed to open but not close, as sealing and healing behaviour was not well characterised. The drainage from the crop model was assumed to be a sum of drainage via the matrix and drainage through the crack. Drainage through the cracks is assumed to be the precipitation multiplied by the proportion of the surface area of the dyke that is cracked, i.e.

$$\begin{aligned} D &= D_{crack} + D_{matrix} \\ &= P(A_{crack} + A_{matrix}) \end{aligned} \quad (4)$$

where A indicated the surface area fraction, D indicates the drainage and the subscripts crack and matrix indicate the cracked and intact portions. This assumes that there is no flow resistance from the crack, nor any interception from the vegetation. As a consequence of the cracking the capacity of the root zone to hold water also reduced (as the soil matrix is then denser), which has a consequence for further vegetation growth as observed by Hasan et al. (2013).

The same approach for calibrating the hydraulic properties used throughout the analysis was taken as used in Jamalinia et al. (2019).

The root zone shear strength was assumed to linearly decrease with the proportion of the surface area of the dyke that is cracked. No accounting for crack direction was made in order to keep relatively simple assumptions and model setup. Calibration of such an assumption for use in real cases needs to be problem dependent.

In Figure 4, an example model output is shown for the dyke shown in Figure 2. It is seen that the area of crack increases early in the analyses as drier conditions than previously observed happen frequently. After 2011, another cracking event is not predicted until 2018. Cracking events can be seen to occur at low root zone water contents, which also coincides with very low LAI. It is interesting to note that in 2018, when very dry conditions occurred and vegetation was observed to be dying, the model again predicts cracking. The maximum water content in the root zone is shown to decline with cracking, which is seen to slow the vegetation growth or encourage it to die-off more rapidly when water is limited. As a consequence the FoS declines in general and still has low peaks during rapid wetting events. Some drainage events are only observed in the cracked analysis, as water can pass through cracks even if the matrix is dry and blocks the water flux, this means cracked dykes can be more vulnerable to extreme wetting events.

An alternative approach to simulating the impact of cracking is the dual permeability (DP) representation. This can allow a computationally efficient simulation of the dynamic exchange between atmosphere, cracks and soil matrix for dykes while maintaining an acceptable computational burden and still explicitly representing the impact of cracks and matrix. Aguilar-López et al. (2020) developed a simple methodology for parameterising the soil water retention curve of DP models to represent cracks in dykes, so that the fast domain responds significantly faster than in the original concept and therefore more similarly to the filling and emptying process of an initially empty crack.

Two types of wetting events were classified for non-coastal dykes: *talus hydraulic loading* (e.g. flood events) and *rainfall* events. For both types of loading, the interaction between cracks and soil matrix and its antecedent moisture content is different. Cracks can work as both fast conduits of water into the dyke and drainage ‘valves’.

For the case of talus hydraulic loading, the representation of a (similar) loaded dyke in time was simulated (i) with a single permeability (SP) with two scenarios (the first with no cracks and the second with the average volumetric hydraulic conductivity including the cracks) and (ii) a dual permeability (DP) simulation. It was shown that the minimum factor of safety achieved is very similar for both types of simulation and occurs one or two days before the minimum drawdown water loading occurred (see Figure 4). However, the effects of the DP model can be better observed for the second part of the loading cycle, where the SP model achieves a lower Factor of Safety due to its lower drainage capacity and higher moisture content retention. Note that while the DP model gives very similar minimum value of safety factor for the drawdown condition, it differs significantly for the max loading condition which happens around 9 days where DP model is FS of 1.38 with respect to 1.30 for SP model, which could be significant for the consequence of a potential failure.

The double peak seen in the model is a characteristic of the dyke situation with a changing free water surface on one side, where the failure mechanisms switches from the inner dyke at high water level to the outer dyke at low water levels. The DP model allows for water to flow from matrix to soil in the case where the inner pressure heads become higher in the matrix domain. This will result in a more realistic behaviour for cracks which are not directly exposed to the water loading but then rather get ‘filled’ by capillary effects.

The model includes the effects of the matrix suction in the vadose zone which contributes positively to the dyke stability and does not include the effects of crack volume variation due to change in the moisture content.

It is seen that in the case of a DP representation, the formulation can directly represent changes in flow behaviour without the calibration of properties used in the previous analysis, so this method can be used to improve computational efficiency.

For the case of rainfall type of events, a different DP model was built (Holstvoogd, 2022) to test the response of cracked dykes with respect to the type of rainfall event as the antecedent moisture content plays an important role in the infiltration rate. Cracks are allowed to close as a function of the saturation of the matrix (i.e. not due to a mechanical calculation). The minimum safety factor for two different simulations of a dyke with the same initial conditions was calculated. Each simulation had the same type of boundary condition in terms of rainfall intensity duration and total volume, with the only difference being the incremental order of the hyetograph as shown in Figure 5. Water which cannot infiltrate is removed to represent runoff.

The results (Figure 5), show that a decremental hyetograph results in a final minimum safety factor which is 0.1 lower than the incremental simulation. This effect occurs due to the fast filling of the cracks which allows water to infiltrate faster into the dike prior to the matrix swelling and closing the fractures, while slow starting infiltration allows the matrix to close cracks prior to heavier rainfall. This confirms the findings of Jamalinia et al. (2020) which indicate that heavy rainfall after a dry period leads to the lowest FoS.

Both wetting event studies have shown how the presence of cracks has an important influence in the minimum safety factor estimation and how minimal changes in the boundary conditions may lead to a different result. Surface cracks not only represent preferential flow paths, but they also represent an increase of the atmospheric interface area. Such increase in combination with the antecedent moisture content of the soil may result in significantly different stability estimation of dykes when compared to steady state conditions.

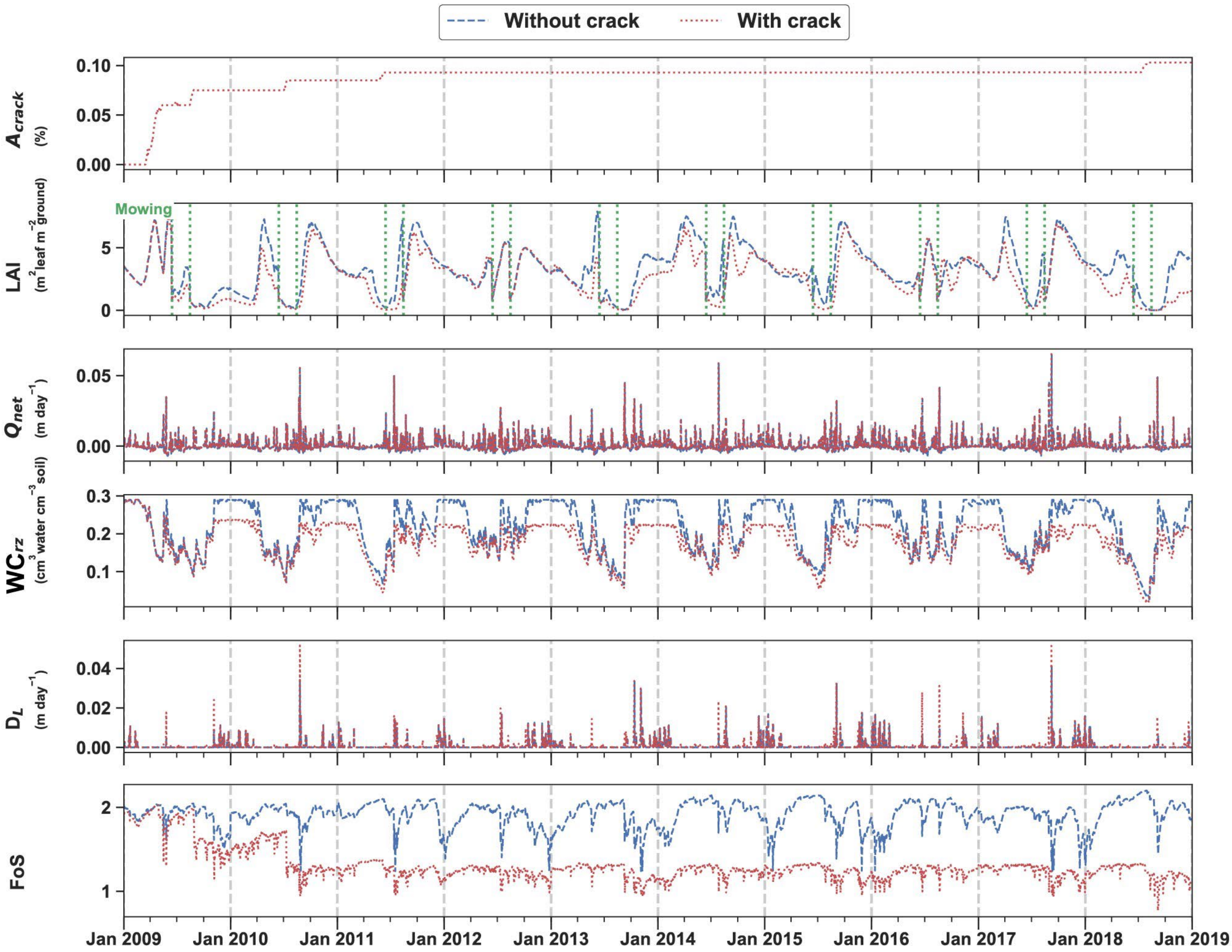

Figure 3. Model output including influence of cracks (after Jamalinia et al., 2020). A_{crack} is the percentage of the surface area of the dyke that is cracked.

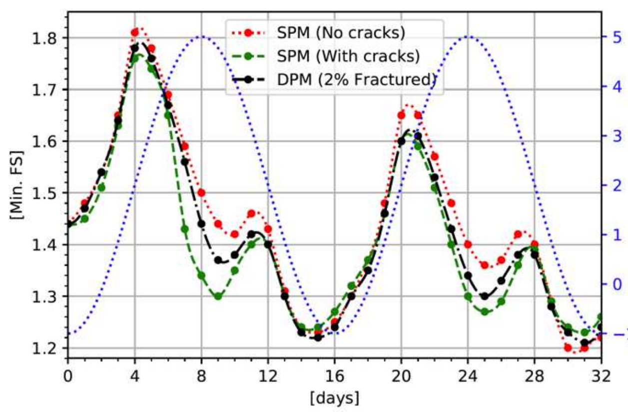

Figure 4. Single permeability (SPM) and Dual Permeability (DPM) finite element model for estimating the minimum safety factor based on the c-ϕ reduction method. Both models simulated using COMSOL Multiphysics.

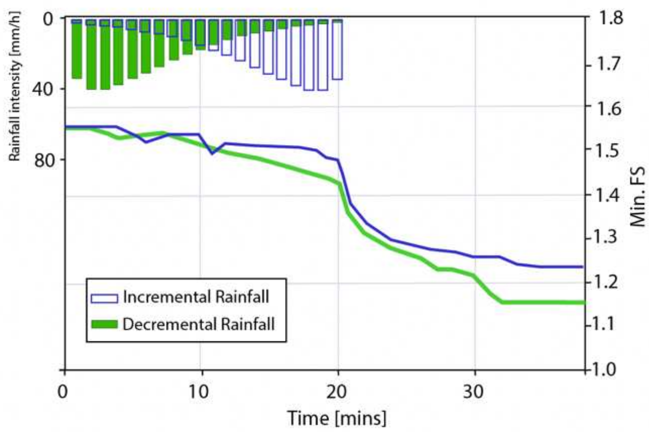

Figure 5. Dual permeability groundwater dyke simulations with different rainfall intensity boundary conditions. Both incremental and decremental hyetographs have same storm duration and same total volumes.

5 CRACK DETECTION AND PREDICTION

The existence of cracks in slopes has been seen to have a significant influence on the stability. Desiccation cracks are mode 1 cracks which occur when the effective stress state in the soil reaches the tensile strength of the material. The tensile strength is not an intrinsic soil property, but is a function of, and evolves with, the water content, suction and the dry density of the material (e.g. Tang et al., 2011). Using Brazilian tests, Lu (2022) determined the tensile strength of a remoulded clay as a function of both water content and dry density. It was shown that the evolution of the tensile strength with water content follows a similar trend as the compaction curve, exhibiting, for all tested dry densities, a maximum value at the optimum water content (Figure 6). This implies that the possibility of a soil cracking, is due to both the current and past weather conditions as well as the soil mechanical state, and may reduce in strength as drying proceeds past a certain level. It has also been observed that drying rate dependence may play a role in cracking, alongside complex stress and strain conditions, which may lead to cracks initiating at or below the surface (Tollenaar et al., 2017).

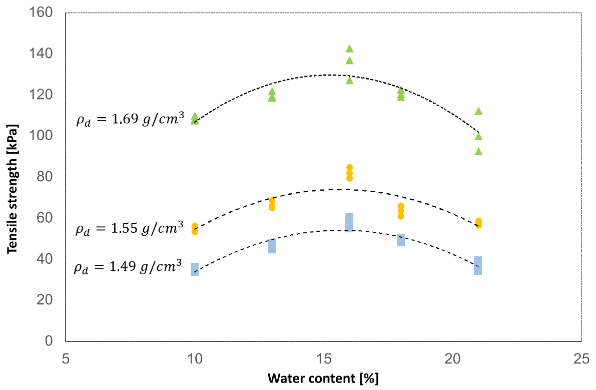

Figure 6. Evolution of the tensile strength of a remoulded clay as a function of water content and dry density (after Lu, 2022).

While the initiation and development of cracks can be followed at the laboratory scale, in practice, the occurrence of cracks which could be relatively thin is challenging to measure. In the Netherlands, dyke inspectors manually inspect dykes, and often returning to locations which have previously been observed to have cracks.

Methods to measure cracks over a significant length or better predict where cracks may occur can allow better analysis of vulnerable locations, or allow enough time to take remedial measures prior to events, such as heavy precipitation, which may cause them to fail.

Large quantities of data of different types on geotechnical infrastructure is increasingly available. This can be on the boundary conditions, i.e. the driving forces described in Section 2, the state or response of the soil or the state of the vegetation. The boundary conditions can be collected from weather stations, which are common and increasing in quantities which can improve local data, or from satellite data, which is also continually improving in resolution providing increasingly local and frequent datasets. The soil state and response can be measured locally using embedded sensors, geophysics, or remotely collected data, e.g. drone or satellite data. Embedded sensors provide one or several points, but with which it is challenging to monitor large stretches of infrastructure, while remotely collected data typically offers a surface response, e.g. surface displacement. Depending on the technology and deployment strategy used, displacement may be available between sub-daily or monthly intervals and at cm to 10s metre grid spacing. Jamalinia et al. (2021) followed up on the theoretical analysis of Jamalinia et al. (2020) and proposed a proxy model based on a detailed finite element analysis, where observable parameters were used to predict the stability in real time. It was shown that the model generally performed well but underperformed when new discrete cracks formed. This was due to the non-linear changes in the model and the difficulty of proxy models to extrapolate. It also highlighted the importance of being able to identify cracks within geotechnical infrastructure.

Two of the main challenges for crack detection in dykes is their dynamic behaviour in terms of their opening and closing and the lengthy nature of both dykes and cracks which makes them difficult to detect. Several remote sensing methods such as thermal camara drones or remote sensing products have been suggested in the past with the aim of detecting the cracks by means of their abnormal thermal behaviour with respect to their surrounding soil. A large portion of the cracks originate from desiccation processes rather than direct mechanical ones. Their opening and closing process makes it difficult to detect them during irregular surveys. It is for this reason that a distributed temperature sensing (DTS) fiber optics (FO) based detection method has been proposed and tested (Duarte Campos, 2022).

A field experiment was performed in which the thermal response along the cable of an existing crack over a peat based clay covered dyke was measured every 15 mins during almost two months, in combination with thermal images every 30 mins (see Figure 6). The initial results from the experiment showed that while there is, as expected, a thermal mismatch between the thermal response along the cable and camara, there is also a mismatch between both measurement devices due to the additional thermal effects of radiation. This behaviour was investigated by de Roos (2022), in which a finite element model was built so that the thermal response of the DTS cable could be studied including the impacts of radiation and wind, to improve detection capabilities. It was concluded that the heat storage and release inside the crack was better quantified by measuring complete daily cycles, expressed in terms of peak to valley daily amplitudes, rather than the instantaneous measurements.

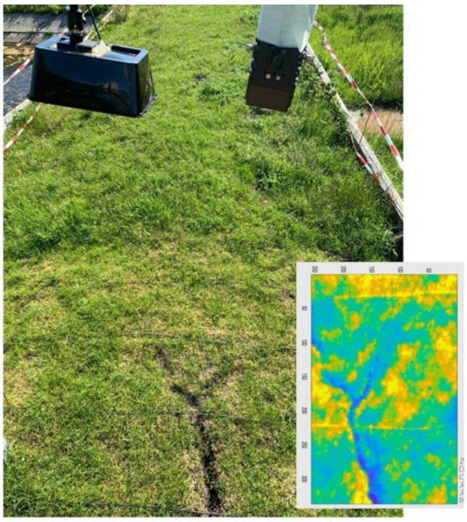

Figure 6. Experimental set-up for crack monitoring based on fiber optic distributed sensing (DTS). A thermal camara was also installed over the crack to collecting thermal images.

Based on the model results, it was found that the effect of solar radiation has a significant influence on the thermal response of the cable due to its high thermal conductivity and radiance absorption with reading differences up to 20°C in situations where the cable was fully exposed to sunlight over the crack with respect to the differences where the cable was laying over the grass. This overestimation is a positive feature for the detection algorithm as it is expected that the cracks may be detected by comparing the errors in the surface temperature measurements of consecutive points with respect to the environment temperature measurements. This can be seen in Figure 7, where the simulated cable measurements over the crack (blue dots) deviate from the 1:1 line with respect to the simulated points over the grass cover; especially during sunny clear days in which peak to peak amplitudes are larger than 5°C.

While distributed sensing, offers the possibility to identify cracks over a substantial length, fully instrumenting the entire geotechnical infrastructure would be a challenge, therefore identifying vulnerable infrastructure would be a major benefit.

Chotkan et al. (2022) targeted identifying vulnerable locations of dykes on a regional level. The investigation utilised an existing dyke inspection dataset from the Netherlands alongside other (publicly) available data to create a machine learning model to identify locations vulnerable to cracking. A random model tree classification method was used (Rutkowski et al., 2014) to classify vulnerable dykes based on possible input parameters.

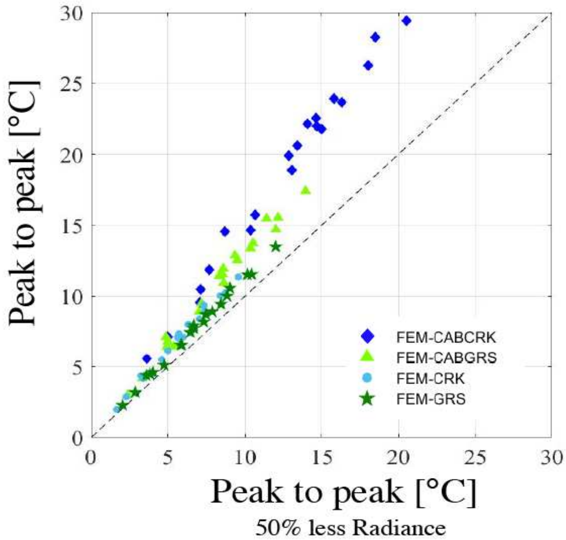

Figure 7. FEM model results from crack and cable. One to one results of calibrated model from experiment vs model with 50% less radiance. Results show that measurement error becomes significantly larger in places where cable is close to and over the crack (blue dots).

The parameters proposed to be tested were: (i) the cumulative precipitation deficit within a time period, i.e. the precipitation minus the potential evaporation; (ii) the soil subsidence rate; (iii) a measure of vegetation greenness, quantified using the normalised difference vegetation index (NDVI); (iv) the soil type of the first soil layer under the dyke; (v) the thickness of (any) peat layer in the soil profile; (vi) soil stiffness and thickness – quantified by soil flexibility; and (vii) the dyke orientation.

One challenge when using observed events in data is the inclusion of negative data. This formed part of the investigation within this work. A successful approach was shown to be the identification of small cracks as negatives. This allowed a level of certainty on the observation, i.e. it is not a negative simply where someone has not inspected, and a level of indication of the impact.

A decision tree was formed from the database, which is shown in Figure 5a. Here the training data is split by differentiating parameters until further discrimination cannot be made. The colour of the nodes demonstrates the ability to detect a positive (more blue) or negative (more orange). In Figures 5b, c and d, hazard maps produced from the model, observed cracks and expert judgement (from experts managing the dykes in the area) are shown. The model is shown to predict (Figure 5b) the cracked locations shown in Figure 5c well. It also highlights a limited amount of other areas which could be vulnerable, where cracks have not (yet) been observed. In comparison to the hazard map created by expert judgement (Figure 5d), the model predicts fewer locations, including noticeably fewer where no cracks have been observed.

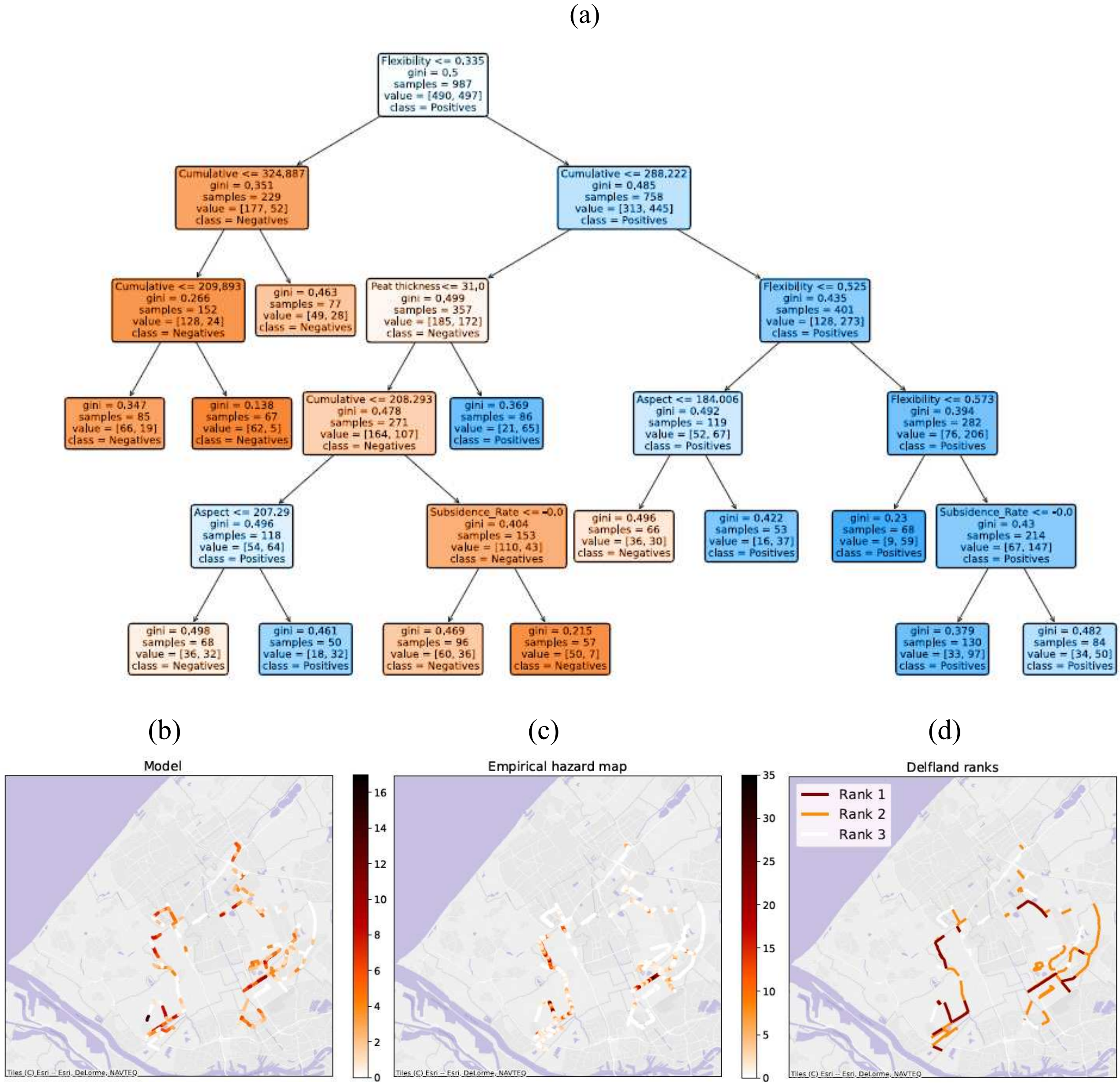

Figure 5. (a) The decision tree model output to predict the vulnerability to cracking, (b) hazard map generated from the model (higher the number represented by the colour bar, the higher the hazard), (c) hazard map generated from observed cracks (number is the number of observations), (d) hazard map generated from expert judgement (Rank 1 has the highest hazard). After Chotkan et al. (2022).

6 ATMOSPHERIC DRYING OF SOIL SLUDGES

In the case of dykes, drought conditions coupled with more extreme rainfall (as increasingly experienced in Europe due to climate change) are an example of soil-atmosphere interaction which has a negative influence on geotechnical infrastructure. A potentially positive impact of soil-atmosphere interaction is the evaporative drying of soil sludges, i.e. high water content soils, which arise due to mining or dredging activities. Such materials are sometimes observed to take many decades to consolidate, and while still liquid remain a hazard. In addition, storing such large quantities of water, vastly increases the storage quantities needed. Land reclamation using finer materials has also been proposed, as there is a global shortage of sand and transport distances can be reduced which reduces carbon emissions.

In atmospheric drying of soil sludges, layers of high water content fine material (e.g. >150% gravimetric water content) are deposited and allowed to dry. Alternative approaches (or sometimes undertaken in addition) are adding a flocculant, mixing with other materials, centrifuging or thermally drying. These other processes can be costly and can have a high environmental impact.

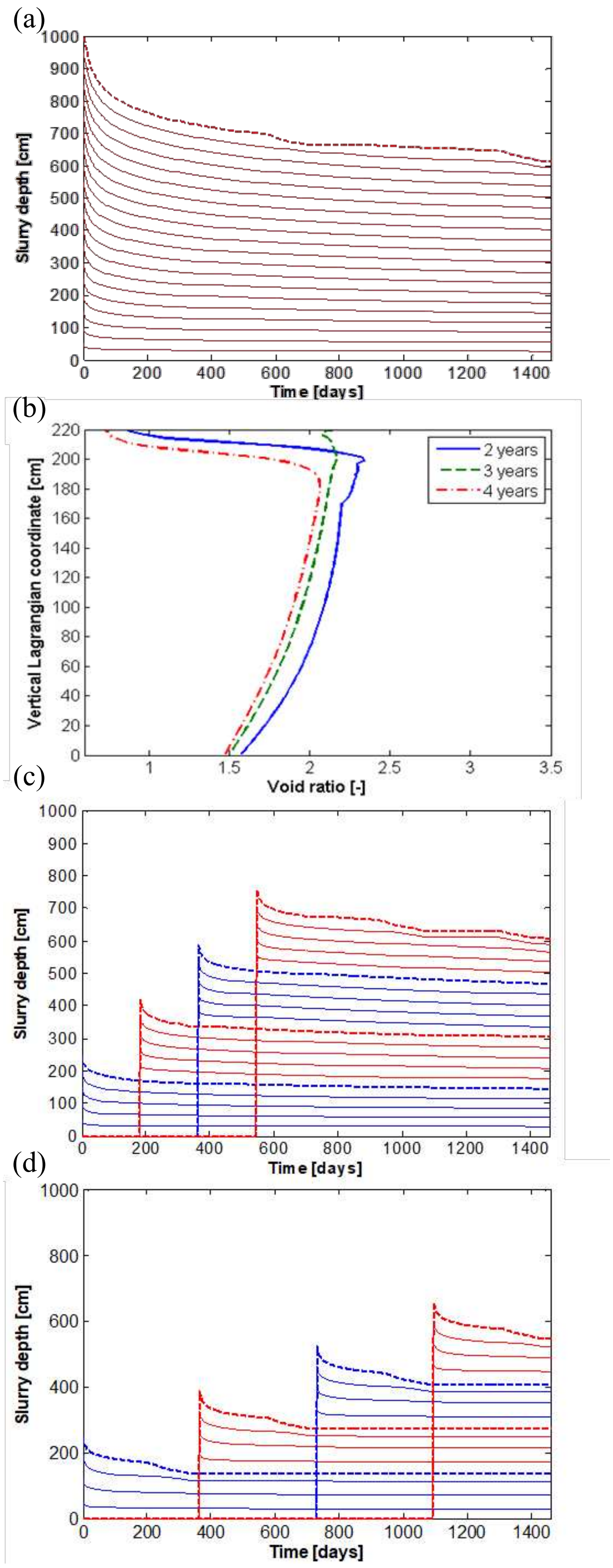

Figure 6. Atmospheric drying results (after Vardon et al., 2015) (a) Settlement against time for a single deep layer; (b) void ratio over depth for a single deep layer; (c) Settlement against time for four layers deposited within one year; (d) Settlement against time for four layers deposited over four years.

The processes occurring during atmospheric drying are mainly consolidation and then evaporation. At the beginning, consolidation is usually dominant, and more water than can evaporate may flow to the surface and can be managed via drainage. Following that, atmospheric drying takes over and the evaporative flux can exceed fluxes due to consolidation. Precipitation may rewet the soil, but due to plasticity the large water contents are not recovered.

When drying, the soil follows first a shrinkage behaviour, where the soil remains saturated, yet the volume decreases. Following this, after further evaporation, the soil can begin shrink less and therefore begins to desaturate. This can be quantified via the shrinkage curve. As the soil first shrinks and then desaturates, two things happen. The soil becomes stronger – which reduces the potential hazard and makes the sludge able to support weight – and the hydraulic conductivity decreases – which reduces the possibility for further consolidation or drying to take place. This process is known as crust formation and limits the depth that drying can occur.

This process was quantified in Vardon et al. (2014, 2015, 2016), using theory developed by Kim et al. (1992), where a single phase consolidation model was demonstrated to be able to simulate field tests of atmospheric drying. In Vardon at el. (2015), an optimisation of the process was undertaken. The same quantity of material was deposited in a different number of layers (between one and four) and a different times of the year.

Figure 6 presents selected results. In Figure 6a and 6b, the results for a single layer is shown. The early transient behaviour is consolidation driven, with a period between around 200-400 days where evaporation is slightly higher than the water flux due to consolidation. At approximately 600 days (the second summer) evaporation drives the water flux and the top surface sharply reduces (Figure 6a). This process is limited to the top ~30cm, which is highlighted in Figure 6b, where a thin layer of low void ratio is observed, i.e. a crust is formed, with a large void ratio immediately underneath. After 4 years, the material has further consolidated, but this is limited and the crust is not significantly further developed.

In comparison two different scenarios of 4 layers of initial equal depth are shown in Figures 6c and 6d. In Figure 6c, the layers are deposited (instantly) every 6 months, whereas in Figure 6d, the layers are deposited every year. In both cases, the first layer is deposited in the winter. In Figure 6c, it is seen by observation of the smooth decreasing depth curve, that consolidation occurs in each layer and evaporation only plays an important role after approximately 900 days. This means that (i) evaporation does not play a role until the third year, and (ii) no crust is formed at the top of the layers. In Figure 6d, in each layer consolidation water fluxes are dominant for around 3 months, followed by a period of evaporative drying. A crust of around 50% of the layer thickness is formed, which substantially increases the strength of the layer and results in more settlement. The approach of depositing the layer such that consolidation can occur for a period of time before crust formation is a strategy where engineering can occur in conjunction with weather conditions.

7 ENERGY GEOSTRUCTURES

Shallow geothermal systems are one of the major success stories for the deployment of low carbon energy sources/stores. In this technology, closed-loop pipe heat exchanges are installed in the ground, which can extract or inject heat into the ground. To reduce costs and install more of these heat exchangers, there has been a significant amount of research into adding such heat exchangers to geotechnical-structural elements, e.g. in energy piles (Brandl, 2006). As these heat exchangers follow the form of the structure, e.g. the pile foundation, they are usually significantly less deep than typical shallow geothermal systems. This means that the soil-atmosphere interaction may play a more significant role.

Energy quay walls are a recent development (Ziegler et al., 2019, Haasnoot et al., 2022) where heat exchanger elements are added to metal sheet piles, which are used to form quays. The sheet piles then are adjacent to both open water and soil, and heat exchangers can be applied solely in the water or in both the soil and water. A field scale test was undertaken recently in de Zweth, the Netherland, where a ~8.5m length of quay was installed as an energy quay wall (Figure 7), with several variants of sheet pile heat exchangers: deep heat exchangers going through first ~3m of water then ~12m of soil, shallow heat exchangers with the depth limited to the water depth and 'add-on' panels which attach externally to existing sheet piles. An initial finite element analysis was undertaken by de Vries (2021) and is shown in Figure 7.

During the test it was seen that the air temperature varies the fastest, the water the second fastest and the soil the slowest. Heat was able to be extracted by up to a factor of 10 more from the water than from the soil, yet reduced significantly when external temperatures dropped. However, even at very cold temperatures, the water was able to provide energy. In the field test, even though the canal did not have any water flow, there was sufficient mixing due to wind and convection to ensure that the heat extraction could remain constant.

The tests also showed that it was possible to store considerable thermal energy in the subsurface, by circulating through the warm surface water during the summer, but that careful planning of use was needed to take advantage of this, as the energy could be lost to the surface water during production when the surface water is reasonably cold.

In this type of energy geostructure, it is essential to consider the soil-atmosphere processes. This is due to its limited depth (<15m) and the surface water.

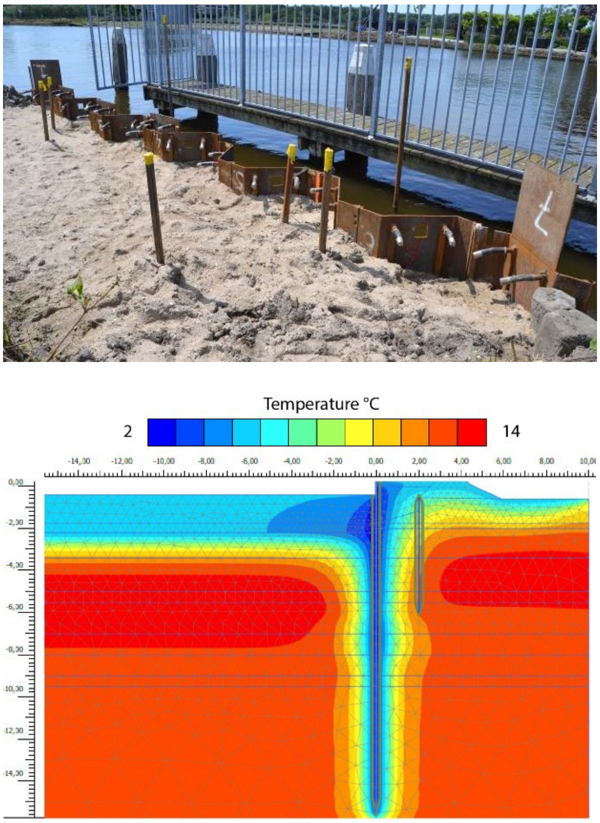

Figure 7. Energy quay wall test. Top: view of the experimental site (after Haasnoot et al., 2022). Bottom: Finite element simulation of the test (after de Vries, 2021).

8 DISCUSSION

Coming to the main question that is posed in the introduction, soil-atmosphere interaction has been shown to be a phenomenon which can influence soils and structures made of soils. It can be both negative, e.g. cause cracking due to droughts and positive, e.g. providing strength due to suction, allowing draining paths to relieve excess pore pressures, providing energetic recharge and providing a driving force to consolidate hazardous material. The answer to whether soil-atmosphere interaction is important, to the authors, is clearly yes. However, it is also clear that the impact that it has and its importance is dependent on the structure, its purpose and its local situation. This means that whether it is unnecessary to include in analyses is not a question that can have a simple answer. It should be considered on a case-by-case basis and assessed whether the impact of soil-atmosphere interaction should be quantified because it is important.

In the view of the authors, assessment of existing geotechnical structures and design of new geotechnical structures, can be enhanced by the consideration of soil-atmosphere interaction. It is thought that investment can be better targeted by doing so. As the processes occurring in soil-atmosphere interaction are continuous and ongoing, simulating impacts cannot be exact; uncertainties will remain. This implies that direct observations, i.e. monitoring, will be needed to confirm predictions, but techniques using available data and remote sensing can be used to direct the in situ monitoring effort.

9 CONCLUSIONS

Soil-atmosphere interaction can play a significant role on several different types of geotechnical infrastructure. The factors and different structures have been explored through this paper, and it is shown that depending on the structure the processes, the geometry and the requirements for the structure determine whether it is needed to be examined in detail. A focus has been placed here on the macro-stability of geotechnical structures. Other infrastructure can also fail via several other mechanisms which are also impacted by soil-atmosphere interaction. In most cases, more in depth knowledge on performance is gained by incorporating soil-atmosphere interaction, yet analyses are complicated. The potential performance benefit or threat needs to be considered to answer whether it should be included in design calculations.

Soil-atmosphere process can be difficult or complex to monitor and model, especially when causing discrete features, e.g. cracks. Indirect monitoring such as using vegetation, coupled with other factors which can be measured or monitored can give data in order to guide inspections.

10 ACKNOWLEDGEMENTS

We gratefully acknowledge the passion and interest of our students and colleagues with whom we collaborated to produce the research upon which this paper is based.

11 REFERENCES

Aguilar-López, J.P., Bogaard, T., Gerke, H.H. 2020. Dual-permeability model improvements for representation of preferential flow in fractured clays. *Water Resources Research* **56**(8), e2020WR027304.

Bordoni, M., Bittelli, M., Valentino, R., Vivaldi, V., Meisina, C. 2021. Observations on soil-atmosphere interactions after long-term monitoring at two sample sites subjected to shallow landslides. *Bulletin of Engineering Geology and the Environment* **80**, 7467–7491.

Brandl, H. 2006. Energy foundations and other thermo-active ground structures. *Géotechnique* **56**(2), 81–122.

Chotkan, S., van der Meij, R., Klerk, W.J., Vardon, P.J., Aguilar-López, J.P. 2022. A data-driven method for identifying drought-induced crack-prone levees based on decision trees. *Sustainability* **14**(11), 6820.

Cleall, P.J., Muñoz-Criollo, J.J., Rees, S.W. 2015. Analytical solutions for ground temperature profiles and stored energy using meteorological data. *Transport in Porous Media* **106**, 181–199.

Costa, S., Cherukuvada, M., Islam, T., Kodikara, J. 2023. Impact of climate change on shallow ground hydro-thermal properties. *Bulletin of Engineering Geology and the Environment* **82**, 16.

De Roos, S. 2022. *Crack detection for dikes using distributed temperature sensing* MSc Thesis, TU Delft. http://resolver.tudelft.nl/uuid:61999eab-1630-43b2-9b49-b2691d630e4e

Di Carluccio, G., Pinyol, N.M., Alonso, E.E., Hürlimann, M. 2023. Liquefaction-induced flow-like landslides: the case of Valarties (Spain), *Géotechnique* Ahead of Print.

Duarte Campos, L., Aguilar López, J.P. 2022. Dike Monitoring comparison between thermal camera and DTS systems for drought induced cracks on dikes. *Proceedings EGU General Assembly Conference Abstracts*, 11657.

Elia, G., Cotecchia, F., Pedone, G., Vaunat, J., Vardon, P.J., Pereira, C., Springman, S.M., Rouainia, M., van Esch, J., Koda, E., Josifovski, J., Nocilla, A., Askarinejad, A., Stirling, R., Helm, P., Lollino, P., Osinski, P. 2017. Numerical modelling of slope-vegetation-atmosphere interaction: an overview. *Quarterly Journal of Engineering Geology and Hydrogeology* **50**(3), 249-270.

El-Zein, A., Airey, D., Yu, B., Esgandani, G.A., Proust, G., Dias-da-Costa, D., Gao, Y., Gan Y., Chen, S. 2021. Self-repair of cracks and defects in clay: a review of evidence, mechanisms, theories and nomenclature. *Acta Geotechnica* **16**, 3741–3760.

Gens, A. 2010. Soil-environmental interactions in geotechnical engineering. *Géotechnique* **60**(1), 3–74.

Golchin, A., Vardon, P.J., Hicks, M.A. 2022. A thermo-mechanical constitutive model for fine-grained soils based on thermodynamics. *International Journal of Engineering Science* **174**, 103579.

Haasnoot, J, de jong, K., Leclercq, V., Bersan, S., de Vries, J., Vardon, P.J., Pantev, I., Stoelhorst, P., Jansseen, R., Bloemers, B. 2022. Energy Quay Walls - theory and initial trial results. *Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering* (Eds. Rahman, Md.M., Jaksa, M.), 4923-2928.

Hasan K., Aanstoos J.V., Mahrooghy M. 2013. Stressed vegetation identification by SAR time series as an indicator of slope instability in Mississippi river levee segments. *Proceedings, Applied Imagery Pattern Recognition Workshop (AIPR): sensing for control and augmentation.* IEEE.

Holstvoogd, J. 2022. *A surrogate model approach to study the effect of rainfall through cracks on the macro-stability of canal dikes*. MSc thesis, TU Delft. http://resolver.tudelft.nl/uuid:bc8cba5c-c77e-4959-b700-b9a0bf4aefe6

Jamalinia, E., Vardon, P.J., Steele-Dunne, S. C. 2019. The effect of Soil-Vegetation-Atmosphere interaction: a numerical study, Environmental Geotechnics. **8**(7), 430-441.

Jamalinia, E., Vardon, P.J., Steele-Dunne, S. C. 2020. The impact of evaporation induced cracks and precipitation on temporal slope stability, *Computers and Geotechnics* **122**, 103506.

Jamalinia, E., Tehrani, F.S., Steele-Dunne, S. C., Vardon, P.J. 2021. A data-driven surrogate approach for the temporal stability forecasting of vegetation covered dikes. *Water* **13**, 107.

Kandalai, S., John, N.J., Patel, A. 2023. Effects of climate change on geotechnical infrastructures — state of the art. *Environmental Science and Pollution Research* **30**, 16878–16904.

Kim, D.J., Diels, J., Feyen, J. 1992. Water movement associated with overburden potential in a shrinkage marine clay soil, *Journal of Hydrology* **133**, 179–200.

Kolditz, O., Görke, U.J., Shao, H., Wang, W. (Eds.) 2012. *Thermo-Hydro-Mechanical-Chemical Processes in Fractured Porous Media: Benchmarks and Examples*. Lecture Notes in Computation Science and Engineering, 86. Springer-Verlag, Berlin Heielberg.

Lu, T. 2022. *Effects of dry density and water content on the tensile strength of remolded Boom Clay: an experimental study.* MSc thesis, TU Delft.

Rutkowski, L., Jaworski, M., Pietruczuk, L., Duda, P. 2014. The CART decision tree for mining data streams. *Information Sciences* **266**, 1–15.

Tang, C.-S., Shi, B., Liu, C., Suo, W.-B., and Gao, L. (2011). Experimental characterization of shrinkage and desiccation cracking in thin clay layer. *Applied Clay Science* **52**(1), 69–77.

Tian, B.G., Cheng, Q., Tang, C.S., Shi, B. 2023. Healing behaviour of desiccation cracks in a clayey soil subjected to different wetting rates, *Engineering Geology* **313**, 106973.

Toll D.G., Md. Rahim M.S., Karthikeyan M. 2019. Soil–atmosphere interactions for analysing slopes in tropical soils in Singapore. *Environmental Geotechnics* **6**(6), 361–372.

Tollenaar, R.N., van Paassen, L.A., Jommi, C. 2017. Observations on the desiccation and cracking of clay layers. *Engineering Geology* **230**, 23-31.

Schapendonk A.H.C.M., Stol W., Van Kraalingen D.W.G., Bouman B.A.M. 1998. LINGRA, a sink/source model to simulate grassland productivity in Europe. *European Journal of Agronomy* **9**(2–3): 87–100.

Vardon, P.J., 2015. Climatic influence on geotechnical infrastructure: a review. *Environmental Geotechnics* **2**(3), 166–174.

Vardon, P.J., Yao, Y., van Paassen, L.A., van Tol, A.F. 2016. Consolidation and atmospheric drying of fine oil sand tailings: comparison of blind simulations and field scale results. *Proceedings, IOSTC2016* (Eds. Sego, D.C., Wilson, G.W. & Beier, N.A.), 396-407.

Vardon, P.J., Nijssen, T., Yao, Y., van Tol, A.F. 2014. Numerical simulation of fine oil sand tailings drying in test cells. Proceedings, *IOSTC 2014* (Eds. Sego, D.C., Wilson, G.W. & Beier, N.A.), 59-69.

Vardon, P.J., Yao, Y., van Paassen, L., van Tol, A.F. 2015. The use of a large-strain consolidation model to optimise multilift tailing deposits. *Proceedings of the Tailings and Mine Waste Management for the 21st Century* (Ed. Nejad, F.R.), 263-270.

de Vries, J. 2021. *Quays rather than boilers. extracting heat from water and soil through energy sheet piles*. MSc thesis. TU Delft.

Ziegler M., Koppmann D., Pechnig R., Knapp D. 2019, Energy sheet pile walls - Experimental and numerical investigation of innovative energy geostructures. *Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering*.