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Monitoring climate induced degradation processes of soft soil dykes in the Netherlands

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ABSTRACT

A large part of the Dutch regional dyke network is classified as drought-susceptible given that both the dyke body and the foundation layers consist of soft organic soils. The erratic weather conditions over recent years, which included prolonged drought, new temperature records and intensified rainfall, are linked to an increased number of accidents related to dyke degradation. As global warming continues to exacerbate extreme weather, there is a growing concern on the impact of changing climatic conditions on this type of regional dykes. Poor understanding of climate induced soil degradation processes poses a serious challenge in the development of adaptation strategies. The challenges are caused by the large variety of interplaying factors, dynamic environmental actions and the complex description of coupled degradation processes with varying spatial-temporal scales. This study demonstrates the potential use of field monitoring to overcome some of these limitations. Field monitoring data on ten Dutch regional dyke sections, with varying geometry, stratigraphy and vegetation are presented. The data provide insight into changes in dyke hydraulic state as a function of atmospheric conditions and allow to infer possible climate induced soil physical degradation mechanisms depending on dyke characteristics. To fully evaluate the impact of degradation on the water protection system, ancillary monitoring data are required, able to quantify the mechanical implications of climate induced state variations. The design of dedicated monitoring set up on three selected dykes, which will serve as representative case studies for the development of geotechnical assessment methods, is eventually presented.

Keywords: climate change; geo-structures; full scale monitoring; organic soils.

1. Introduction

The deltaic environment of the Netherlands is protected against flooding by a large network of dykes. A majority of this dyke network, referred to as regional dykes, originates from the historic practice of land reclamation, with both dyke body and foundation consisting of soft soil deposits, such as clays, peats and silts (Fig. 1). Peats are composed of accumulated organic matter from vegetation, which may include pieces of wood and various types of fibers. Also clayey deposits have varying degrees of organic content, and as a result of their composition, these peaty and clayey soils exhibit high porosity, high volumetric water content, low density and large compressibility (Den Haan and Kruse 2007). In response to climatic or anthropogenic loads, these soils can show significant alterations in soil fabric (Zhao and Jommi 2022), ultimately affecting the stability and serviceability of earth geo-structures. Accordingly, approximately half of the 14.000 kilometres regional dyke network necessitates biannual inspection and maintenance to ensure structural integrity.

Past incidents demonstrated the potential vulnerability of soft soil regional dykes to environmental actions. In 2003, a large dyke failure occurred in Wilnis during a period of long-term drought as a result of the loss of shear resistance from desiccated peat (Van Baars 2005). Mid-summer 2021, another peaty dyke failed with a large failure wedge that passed through the clayey and peaty foundation layers. Besides these failure events, the rise in degradation signs, including desiccation cracking and settlements, can be related to anomalies in recent years climatic conditions.

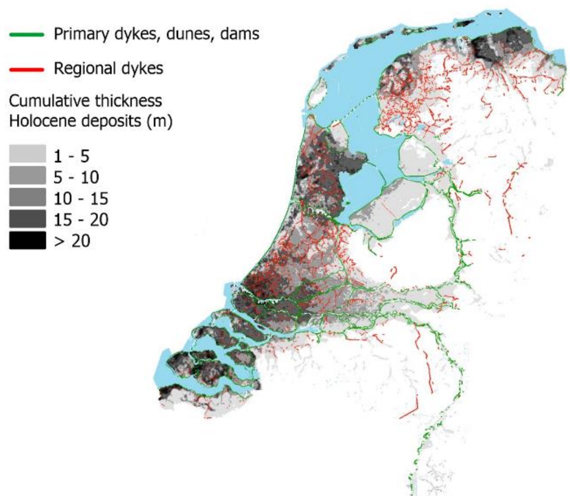

Figure 1. Map of the Dutch dyke network with indication of overall layer thickness of Holocene soil deposits.

As global warming continues to exacerbate extreme weather, the possible impact of climate change on existing geo-structures has been gaining increasing international attention over the past decade. Contributions addressing the implications of climate change on stability of geo-structures have been given by Clarke et al. (2006), Vardon (2015), Robinson and Vahedifard (2016), Tang et al. (2018) and Insana et al. (2021), amongst others. Despite growing attention, findings are not translated to straightforward ready-to-use assessment methods for engineering practice (Vahedifard et al. 2022). Challenges arise from the large variety of interplaying factors governing climate-dyke interactions, such as the non-linear dynamic character of climatic and environmental actions, and the complex description of coupled soil degradation processes with varying spatial-temporal scales.

This paper explores critical aspects related to the stability of soft soil regional dykes in the Netherlands. As a starting point for this exploration, field data of an ongoing monitoring project, the *Drought Monitoring* Project, is presented to identify in-situ hydraulic variations as a function of weather conditions for a variety of regional dykes. Interpretation of this data underscores the necessity for additional monitoring initiatives. To this end, the study proposes complementary field monitoring to three representative dyke bodies within the Drought Monitoring Project. For a specific case study, the design of ancillary field monitoring is illustrated and preliminary monitoring data are presented.

2. Problem statement

2.1. Characteristics of drought-susceptible regional dykes

In 2020, the Drought Monitoring Project was initiated by the Dutch foundation for research on regional dykes (STOWA), with the primary aim to support inspections of drought-susceptible dykes in the Netherlands. Ten dykes, with varying geometry, stratigraphy and vegetation were selected for the monitoring project. Fig 2. provides a cross-sectional impression of the monitored dykes. It can be inferred that many dykes have a limited crest height and a gentle slope. Dykes typically have canals and ditches adjacent to the crest and toe, respectively, with artificially controlled water levels, which vary only a few centimetres a year. In addition, the composition of the dyke body may vary strongly over the cross-section. In depth, the composition and cumulative thickness of the prevailing fine grained Holocene foundation layers range from more than 20 meters (Duifpolder, Groeneveldse Molen, Molenlaan) until only 7 meters (MT-Polder) before a Pleistocene sand layer is encountered.

2.2. Soil degradation mechanisms

In the analysis of historic failures it was observed that failure incidents often concerned shallow-slope dykes with deep seated failure planes, triggered either without clear load cause, or by an anomaly in weather conditions (Boylan et al. 2008; Van Baars 2005). This observation indicates potentially overlooked or misunderstood effects of in-situ environmental actions on the dyke macro-stability. These effects may be twofold, including, on the one hand, ongoing deterioration mechanisms affecting the soil fabric over the lifetime of the geo-structure and, on the other hand, an exacerbating impact when the geo-structure is subjected to unprecedented pressure (or suction) levels (Briggs et al. 2019; Stirling et al. 2021).

In the current environmental conditions, the main dynamic action on Dutch regional dykes follows mostly from annual climatic cycles at the soil boundary, as surficial water levels of adjacent waterways are artificially controlled. Following atmospheric conditions, the vegetated soil surficial boundary is constantly subjected to variable saturated conditions and temperature fluctuations. Depending on the suction stresses, either permanent or temporary soil shrinkage and swelling occurs with consequential impact to soil properties relevant for the water storage capacity and the mechanical response in the unsaturated zone (Te Brake et al. 2013; Chao et al. 2023).

Besides annual cycles in the unsaturated zone, variations in pore pressures inside the dyke body and foundation layers can be triggered by changes of both the top and the bottom boundary conditions, depending on the environmental stress. The top boundary condition will depend on the unsaturated response of the upper cover layer, which controls the position of the phreatic line. The bottom boundary condition follows from subsurface hydrology, in particular the pore pressures in the Pleistocene sand foundation layer. Especially for dykes in low-laying areas this aquifer can exert significant uplift water pressures to overlaying Holocene fine grained deposits. Additionally, inherent to the Dutch soft deltaic deposits, dyke bodies are constantly subjected to large creep settlements, which continuously modify the dyke geometry.

2.3. Potential climate change impact

Future climatic projections in the Netherlands include more extreme weather conditions, such as prolonged drought, new peak temperatures, increased rainfall, and erratic weather changes. Due to the presence of organic matter, some of the Dutch deltaic soils can be especially vulnerable to new climatic extremes, and permanent alterations of soil fabric might occur once subjected to new ranges of pressure (or suction) levels. However, such mechanisms may also occur for low organic, low active soils, often used as embankment covers, as investigated by, e.g., Azizi et al. (2020) for a silty-clay subjected to various drying-wetting cycles.

Increasingly dryer and wetter conditions are expected to alter the water storage system both at the surface and within deeper soil layers. As a consequence, artificial control of surficial water levels may become less sustainable, and alterations in the sub-surface hydrology are expected. However, it is not straightforward to predict these changes given the complicated sub-surface regime to be analysed. Knowledge uncertainty on the actual boundary conditions emphasizes the potential added value of field monitoring.

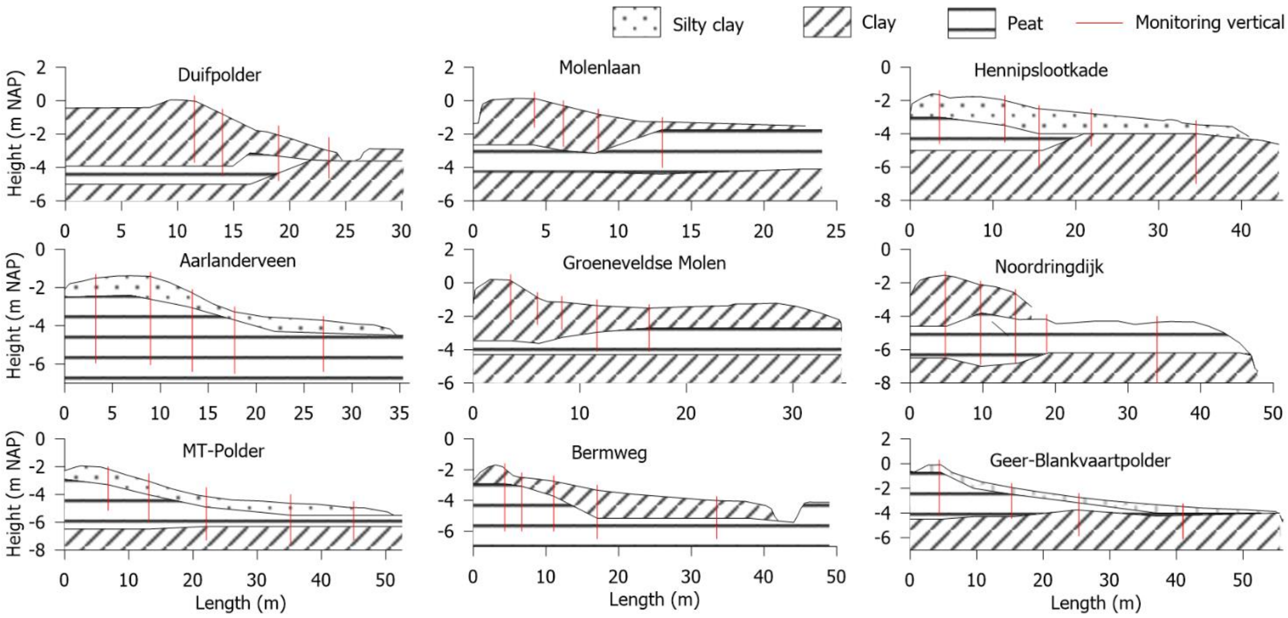

Figure 2. Cross-section of monitored regional dykes.

3. Monitoring data

3.1. Monitoring description

The monitoring configuration of the Drought Monitoring project was designed to quantify in-situ hydraulic variations in the dyke body as a function of weather conditions (Strijker 2023). Ten dykes, with varying geometry, stratigraphy and vegetation (Fig. 2), were instrumented with measurements verticals distributed from the crest to the toe. Each measurement vertical contains moisture content sensors, distributed from the root zone (20 cm depth) until 100 or 150 cm depth, followed by one or two standpipes according to the dyke stratigraphy. The typical monitoring scheme is presented in Fig 3. Piezometers are equipped with automatic divers set to a measurement frequency of every hour, equal to that of the moisture content sensors. Basic sensor specifications are given in Table 1.

In the following sections, data of the sensors are presented for the monitoring period from spring 2020 until the 1st of December 2023. Meteorological data are sourced from the KNMI weather station in Rotterdam. The precipitation deficit is used as a proxy for drought-stress, which is a common practical measure to guide visual inspections of soft soil regional dykes in the Netherlands. In the following elaborations, the precipitation deficit is calculated as the cumulative daily difference between precipitation and reference crop evapotranspiration, from the onset of vegetation growth season (1st of April) until the end of October. Reference crop evapotranspiration is determined by KNMI using a modified Makkink method (De Bruin and Lablans 1998).

3.2. Global moisture content

Fig. 4 shows the global average volumetric moisture content at various depths, along with the cumulative water balance.

Table 1. Sensor specifications

	Range	Accuracy	Operating Temperature
Automatic divers	0 - 10 m	± 0.5 cm H_20	0 - 50 °C
Moisture content sensors	0.00 - 0.70 m^3/m^3	± 0.03 m^3/m^3	0 - 60 °C

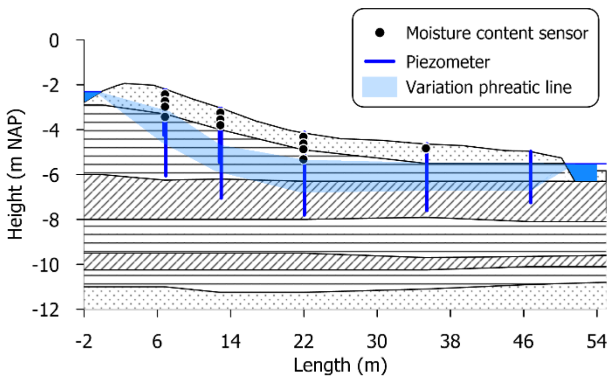

Figure 3. Cross-sectional view of a monitored dyke section.

To obtain the global moisture content variations, data from sensors across all monitoring locations are grouped and averaged based on installation depth.It can be seen that moisture content cycle exhibits clear seasonal variations, which is most prominent in the root zone (20 cm below soil surface). During spring and summer, soil moisture loss progresses over depth. The patterns in moisture loss coincide well with the development of annual precipitation deficit, although moisture losses can initiate well before the onset of growth season. It can be noted that the actual level of precipitation deficit only partially reflects soil moisture deficit. This is particularly evident during the summer of 2021, when, despite low precipitation deficit, moisture loss is still apparent beyond 100 cm depth. Looking at the moisture loss patterns in the years 2020 and 2023, minima in annual moisture levels occurred in spring, whereas the annual maximum precipitation deficit was experienced in summer.

While moisture losses in spring occur more gradually, there are relatively fast transitions at the end of summer towards winter conditions, in which the former unsaturated zone closely reaches field capacity. Also during winter, however, moisture content responses reflect a somewhat sensitive response to climate conditions. The yearly maximum water content slightly varies each winter, which can be linked to atmospheric temperature levels and surplus in precipitation.

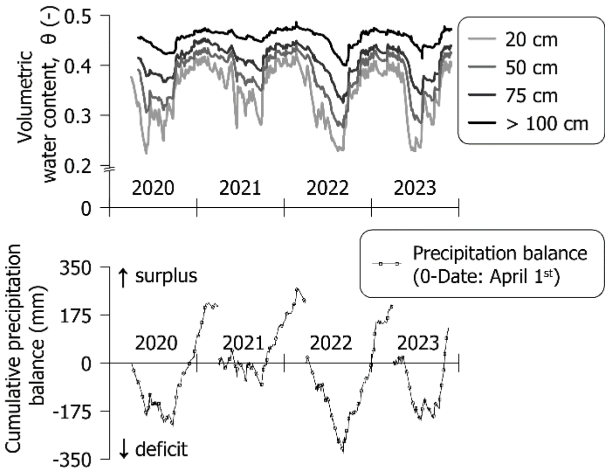

Figure 4. Moisture content at various depths averaged over 10 monitoring locations with precipitation deficit, set to zero at the annual start of growth season (April 1st).

3.3. Soil moisture content per location

Comparing the response of individual dykes gives further indications on which dyke characteristics are relevant on the observed hydraulic variations. Fig. 5 presents moisture content variations of sensors at three selected representative locations in the root zone (20 cm depth) and at a depth of 75 cm in correspondence of the crest of each dyke. For the sake of brevity, the data from the other measurement verticals are not reported here, however the chosen ones are representative of the top soil moisture variations everywhere in the upper layer, from the crest to the toe. MT-Polder and Bermweg have regular grass covers, contrarily to Duifpolder which is heavily vegetated. To compare the measurements from the different sites, the data are plotted as deviations from the average moisture level observed during the monitoring period.

Looking at the response of the individual sensors, it is clear that the local soil surficial response can significantly deviate from the average trend presented in Fig. 4. Looking at the sensor response over depth, it is observed that the root zone (20 cm) is highly dynamic, and deeper sensors (75 cm depth) may be better reflective for actual meteorological conditions. The dynamic soil moisture response in the root-zone can be attributed to the interplay of various local dyke characteristics, like the local soil conditions and the type of vegetation, relevant for the soil suction generation in the unsaturated zone.

Although most of the top soils consist of silty-clayey material, the observations suggest a correlation between particle size distributions and soil moisture levels, with high variations observed in soils containing a high percentage of silt (Duifpolder, MT-Polder), and more limited variations observed for a top layer with high clay content (Bermweg).

For heavily vegetated dykes (similar to Duifpolder) stronger anomalies in moisture declines can be differentiated compared to dykes with regular grass cover. For instance, minima in moisture content in the years 2020 and 2023 might indicate higher soil moisture demand from vegetation growth in spring. The differences between these two locations, however, suggest a dependency of root water uptake from soil composition.

Finally, from Fig. 5, a difference in field capacity is recorded by both sensors at the MT-Polder, though at different years. It is worthwhile noting that a large deformation crack was detected at this dyke location in the summer of 2022. The moisture content anomalies could indicate local changes in the soil physical state, affecting both the water storage potential and the soil geotechnical properties.

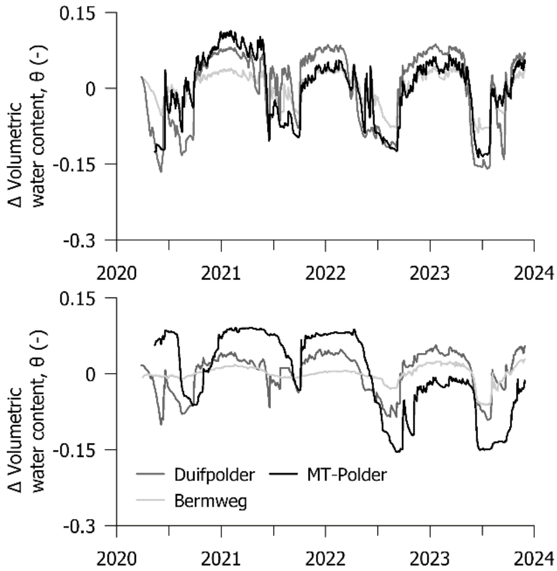

Figure 5. Moisture content variations of individual locations of (top) root zone and (bottom) at a depth of 75 cm below soil surface.

3.4. Piezometers

Piezometers ranging from crest to toe allow to create a cross-sectional view of the position of the phreatic line along the clayey or peaty layers in the dyke body, together with its variation during the year. Water levels in adjacent water ways determine the average position of these phreatic lines, as illustrated in Fig. 3. In addition, dyke geometry is of great importance, as can be inferred from Fig. 6, which presents the piezometric response of Groeneveldse Molen (gentle) and Noordringdijk (steep), respectively.

For dykes with steeper slopes (Noordringdijk, Duifpolder) the overall hydraulic gradient between crest and toe is higher, but variations in the piezometric response along individual standpipes were observed to be lower compared to those alongside gentle slopes.

In the absence of a prevailing geometry effect, measurement verticals along gentle slopes show a clear correlation between moisture content and hydraulic head. This is illustrated in Fig. 7 which presents the monitoring data of the mid slope measurement vertical at Groeneveldse Molen. The figure shows that the seasonal variations in hydraulic head initiate from the moisture fluctuations in the unsaturated zone, with the driving signal over time being the most surficial sensor at the soil-vegetation-atmosphere boundary.

The soil composition is another important characteristic for the dyke hydraulic response. Out of all monitored regional dykes (Fig. 2), the piezometric head at Bermweg limitedly varies due to the low permeable clay cover. Contrary to this, the largest fluctuations in hydraulic head are observed for dykes covered with more permeable silty-clayey top layers, such as the MT-Polder.

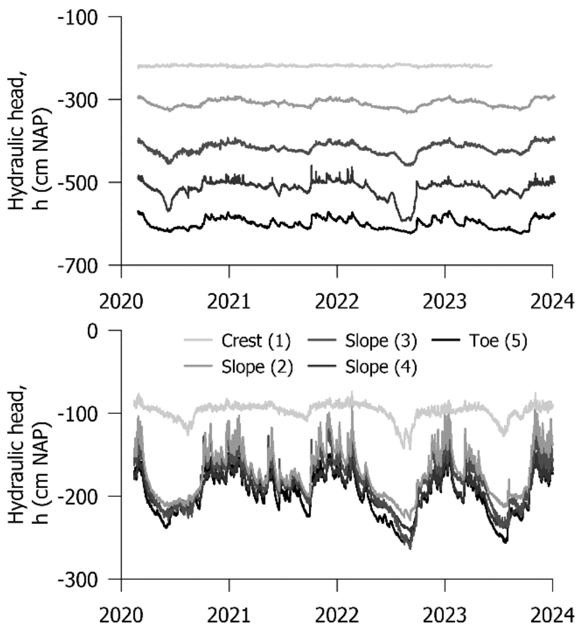

Figure 6. Pore pressures recorded along cross-section of (top) Groeneveldse molen and (bottom) Noordringdijk.

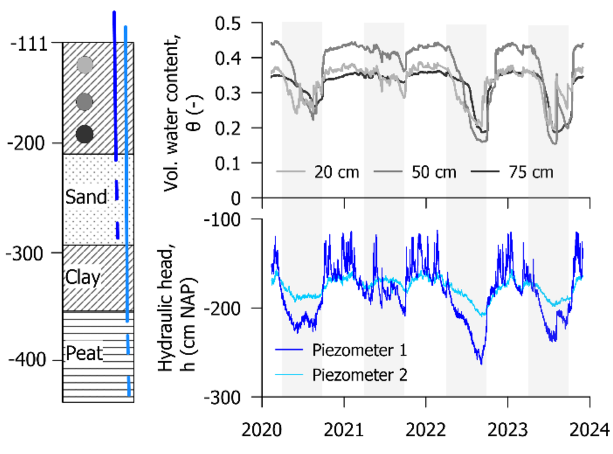

Figure 7. Monitoring data of measurement vertical 3, Groeneveldse molen.

4. Design of additional field monitoring

4.1. Selection of case studies

From the observed differences in the hydraulic response of different dykes, it can be foreseen that the impact of increasingly extreme climatic conditions will have different relevance for each dyke, depending on the prevailing mechanical response of different dyke typology. Hence, a tailored design of additional site-investigation and monitoring per location is desired.

Depending on the expected deformation, as a consequence of moisture content and piezometric surface variations, different monitoring configurations have been designed for three paradigmatic dyke types.

Three locations have been chosen at Duifpolder, Hennipslootkade and MT-Polder. The three locations have been selected based on the identified characteristics that are potentially relevant in climate-dyke interaction, namely, soil stratigraphy, dyke geometry and vegetation.

MT-Polder is a peaty dyke and has been selected because of potential stability issues as inferred from deformation cracking in the summer of 2022 and yearly changes in the moisture content response. Duifpolder has been selected to investigate the response of steep clayey dykes. This dyke has some organic matter in the upper layers, a rather thick marine clay foundation layer and a steep dyke geometry. Contrarily to these characteristics, Hennipslootkade has a gentle slope, consists both clay and peat in its dyke body, and has a relatively shallow Pleistocene sand layer in a water rich area. The latter has been chosen because is expected to be one of the most sensitive to shrinkage and swelling as a consequence of the climate stresses.

4.2. Monitoring the deformation

Out of all ten monitored locations, Hennipslootkade showed the largest hydraulic variations. Due to its gentle and heavy vegetated dyke surface, soil-vegetation-atmosphere interaction is expected to drive significant deformation over the year. Due to the gentle slope of the dyke, deformations are expected to occur primarily in the vertical direction. The design of the monitoring configuration aimed at optimising the information to infer timely variations in pore pressure, caused by the soil-vegetation-atmosphere interaction, the changes in the surficial water levels, the pressure head in the shallow Pleistocene sand together with the corresponding deformation of the soft soil deposits.

To investigate the subsurface conditions prior to the monitoring design, cone penetration tests (CPTu) were performed in the dyke cross-section (Fig. 8). Mid-slope, the dyke body mainly consists of peat, overlain by a small clayey-silty top layer. Towards the toe, a variable organic clay layer is found, strongly mixed with silt and peat. Contrarily to the dyke body, the foundation layer is fairly homogeneous.

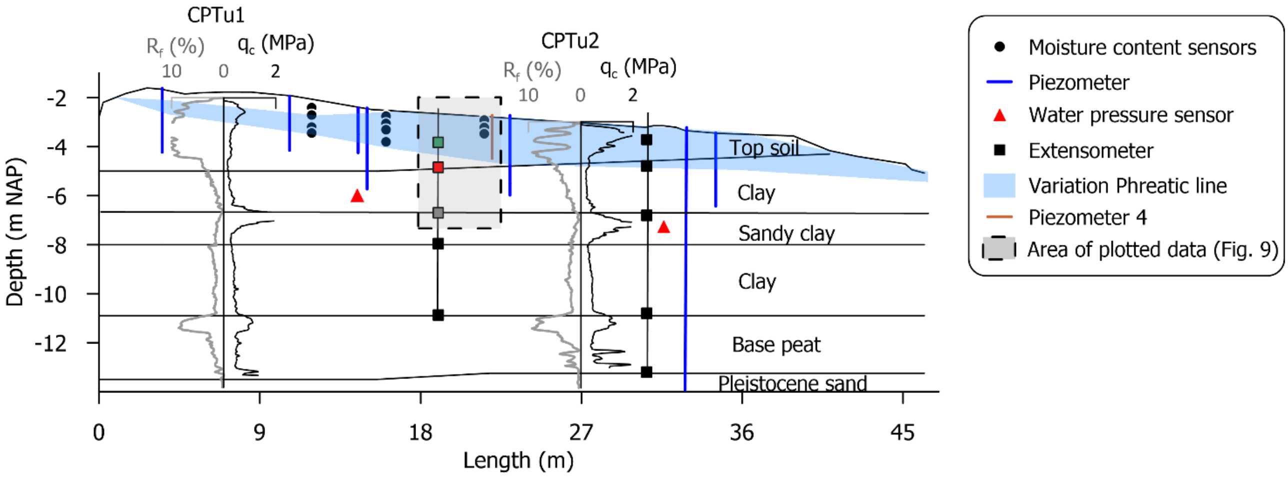

Figure 8. Hennipslootkade: cross section monitoring configuration.

The overall monitoring design is illustrated in Fig. 8. To complement information on the soil hydraulic profile, it was chosen to install a standpipe in the Pleistocene sand layer, and a water pressure sensor in the intermediate sand layer. In addition, two extensometers rods were placed mid-slope and at the toe, each with five anchors. The first anchors of the extensometer rods were placed in the surficial peat and organic clay. Deeper anchors were placed at soil layer transitions, so that the vertical displacements of individual layers can be derived by the relative differences between anchors. Soil samples were retrieved along the installation of the extensometers, which will be used in laboratory tests, aimed at conditioning the interpretation of the in-situ data, once enough information will be collected on site.

4.3. Preliminary monitoring results

The ancillary monitoring started on the 15th of October, 2023, and selected preliminary results from the monitoring data are collected in Fig. 9. Although the monitoring period is still short, the collected data already allow appreciating the clear transition from summer to winter conditions, typically occurring in October. The water content over depth, as well as the water pressures suffered a rather fast increase. Correspondingly, displacement were recorded over all extensometer rods, indicating swelling of each individual soil layer. In Fig. 9, data for displacements are reported relatively to the deepest anchor on the rod.

The upper layer, having the largest organic content, contributes the most to the swelling process. However, it is worth noting that small vertical displacements are observed also in the deeper clay. When the variation of the hydraulic head almost levels off in the period November-December, the surficial extensometers indicate a clear response to fluctuations in moisture content and hydraulic head. Future deeper insight into the monitored data over the year will allow not only quantifying the amount of deformation triggered by climatic stress, but also their time delay.

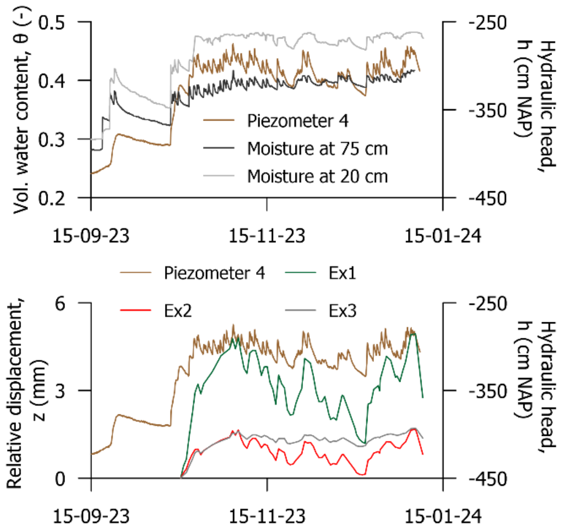

Figure 9. Preliminary monitoring data at Hennipslootkade.

5. Conclusions

Data of the Drought Monitoring project showed that the hydraulic response of regional dykes may be quite variable, depending on various dyke characteristics, including geometry, vegetation, and soil composition. Geometry is the determinant factor for the piezometric gradients over the dyke cross-section. However, past failure events mostly affected dykes having relatively high organic content and gentle slopes, which suggests that the latter can be especially prone to the consequences of increasingly extreme soil-vegetation-atmosphere interactions. The collection of monitoring data on moisture content, pore pressure and deformation, will enable the quantification of the in-situ hydromechanical response, and identifying anomalous response, which may indicate possible soil dangerous degradation mechanisms. Continuation of field monitoring will serve in enhancing the understanding of the climate-induced coupled hydromechanical dyke behaviour, and will allow improving the inspection, the assessment and the maintenance of the regional dyke system in the future engineering practice.

Acknowledgements

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