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DOI
10.1051/e3sconf/202564202020

Publication date
2025

Document Version
Final published version

Published in
E3S Web of Conferences

Citation (APA)
De Wolf, I., Muraro, S., & Jommi, C. (2025). Time series analysis of atmospheric-driven hydromechanical history of soft soil geo-structures. *E3S Web of Conferences*, *642*, Article 02020. https://doi.org/10.1051/e3sconf/202564202020

E3S Web of Conferences **642**, 02020 (2025) https://doi.org/10.1051/e3sconf/202564202020
EUNSAT2025 + BGE

Time series analysis of atmospheric-driven hydromechanical history of soft soil geo-structures

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Abstract. Changing climatic conditions present an emerging threat to geo-structures. Climatic scenarios for the Netherlands indicate rising temperatures and larger variations in the atmospheric water balance. Consequently, geo-structures will be subjected to greater annual pore pressure variations and unprecedented stress levels. A particular concern is the impact of these changing conditions on the geotechnical performance of regional dykes, which are composed of and founded on organic soft soil layers susceptible to degradation. Given that changes in weather patterns are already observable, investigation of current in-situ soil state variations can provide valuable insight into the geotechnical response under future intensified environmental conditions. This study analyses in-situ monitoring data from a shallow-slope dyke system in the Netherlands to assess the persistence of atmospheric-driven pore pressure fluctuations in the dyke body and foundation layers. By correlating local weather conditions with soil response, the study identifies atmospheric events that trigger temporary or permanent variations in soil state, providing a guidance to address the consequences of possible future climatic events, which may compromise the geotechnical performance of soft soil dykes.

1 Introduction

The Dutch regional dyke system has a total length of about 14.000 km, of which the majority consists of and is founded on clayey, peaty and silty deposits. Due to soil-atmosphere interaction, the hydraulic head of surficial soft soil layers can vary significantly relative to the overall height of the dyke structure. As an inherent characteristic of the soft soil fabric, cyclic climate-driven stress variations can induce substantial changes in the porous soil skeleton, impacting its water storage capacity, mechanical strength and stiffness [1, 2]. Past failure incidents demonstrated the potential consequences of extreme climate conditions to the serviceability and stability of geo-structures [3]. To early detect possible manifestations of drought-induced failure mechanisms, dyke inspection is carried out based on atmospheric indicators, such as the precipitation deficit. However, increasingly extreme weather conditions in the recent years have highlighted a potential mismatch between such indicators and in-situ geotechnical dyke response, which exacerbates the need to improve the geotechnical assessment of climate-dyke interactions [4, 5].

Challenges in this assessment arise from the complexity of the dynamic coupled processes ruling the response of the system, particularly at the soil-vegetation-atmosphere interface [6]. However, the geotechnical response to in-situ climatic conditions is determined by many features, including the soil stress history and the soil state at the onset of the climatic event. To complete the description of the system, all boundary conditions, including sub-surface geohydrology, surficial water management and land-use, are needed. Consequently, the formulation of geotechnical models is associated with modelling choices which require large amount of information on boundary conditions and soil conditions, which might not be readily available. In this respect, field monitoring data represents a valuable source of information to assess the relevance of the different processes on the geotechnical response of the system [7].

This work presents the analysis of multiple-year monitoring data of atmospheric conditions (rainfall, evapotranspiration) and hydromechanical variables (soil moisture, piezometric head and layer deformations) of soft-soil regional dyke structures in the Netherlands. The study is part of a combined monitoring effort of various research projects in the country to address the concerns on the durability of the dyke system. At first, monitoring data is presented, followed by the time series analysis of annual soil drying and wetting patterns for the time period 2020 – 2025. For a specific site, these findings are integrated with data on hydraulic head and soil deformation collected in the dyke body and in the subsoil over 2024 and 2025. Intra- and inter-annual hydromechanical trends are correlated with time-series on atmospheric precipitation balance, which highlights the response pattern of the regional dyke.

The study is aimed to provide recommendations able to support the development of an effective modelling strategy, to evaluate dyke geotechnical stability over time under multiple-year climate conditions and including possible increase in the climatic pressure.

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2 Monitoring data

2.1 Physical framework

Fig. 1. presents an impression of a soft-soil regional dyke structure, along with the zone subjected to variably saturated conditions as a result of soil-atmosphere water exchanges. Climatic models for the Netherlands predict a rise in average atmospheric temperature in all seasons, leading to an intensification of rainfall events, heat waves and faster transitions of weather conditions [8]. These changing atmospheric conditions imply a shift in water exchanges at the top soil boundary. However, potential effects of climate change are not limited to the top boundary only. Changes in weather patterns, sea-level rise and river discharges pose an overall shift in the geohydrological water balance. From the viewpoint of the regional dyke system, this implies potential stronger head changes in surficial water bodies and subsurface layers, therefore affecting both lateral and bottom hydraulic boundary conditions as well.

Geotechnical variables, such as soil moisture, pore pressure and deformations, can indicate the hydromechanical response of the dyke body and its foundation layers. Upon loading conditions that fall within a reversible regime, the structure exhibits only temporary alterations of state variables, such as swell-shrinkage behaviour. Multi-year cyclic loading and the occurrence of unprecedented stress levels, for instance by intensified atmospheric water exchanges, can induce permanent alterations to the soil fabric, propagating soil cracking, increased soil settlements and alterations in soil moisture and hydraulic head as illustrated in Fig. 2A. In order to understand and predict climatic impact on the geotechnical response, it is essential to identify these temporary or permanent changes in the soil state. Long-term monitoring data, collected under varying atmospheric conditions, are providing relevant information to this purpose.

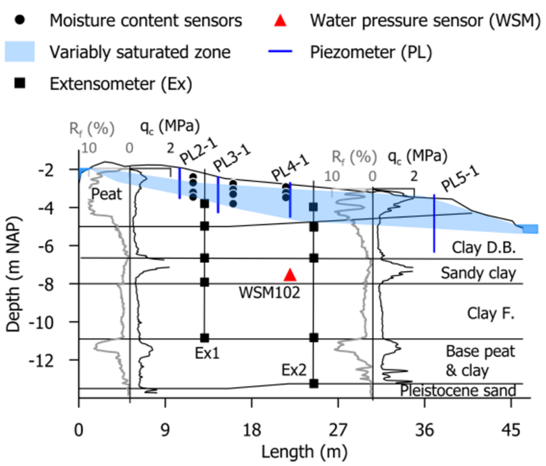

Fig. 1. Monitoring instrumentation at the Hennipslootkade.

2.2 Hydromechanical monitoring data

With this objective in mind, a field monitoring project, called the Droogtemonitoring, was initiated in spring 2020. This project concerns the monitoring of ten regional dyke sections with varying geometry and stratigraphy [9]. The hydraulic monitoring consists of moisture content sensors in the unsaturated zone and piezometers with automatic divers in surficial dyke body layers, distributed from crest to toe as indicated in Fig. 1. As typically observed at all locations, the piezometers at mid-section of the dyke, further away from the side channels, show strong variations in hydraulic head induced by the climatic top boundary.

For a selection of three regional dykes the field monitoring was extended at the end of 2023 to assess vertical and horizontal deformations by means of extensometers and inclinometers [7]. In this paper, the extensometer data at one location, *Hennipslootkade*, is discussed. The cross-sectional profile of the dyke is presented in Fig. 1. The peaty dike was subject to severe reconstruction in 2012. Therefore, the stratigraphy of the top soil layer differs between the mid-slope (peat) and toe (anthropogenic clay), as reflected by the two CPT profiles. To account for the variation in soil composition, both sections are equipped with extensometer rods.

2.3 Atmospheric conditions

Data from KNMI weather station Rotterdam for the monitoring period of 2020-2025 are summarized in Fig. 2B. The annual precipitation deficit is typically determined for growth season (April 1st till September 30th) as the cumulative difference between evapotranspiration [10] and rainfall.

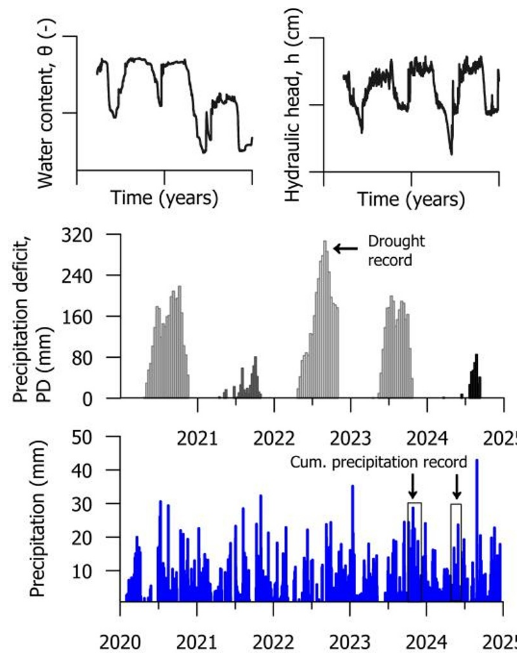

Fig. 2. A) Exemplary long-term monitoring time series. B) Weather data in the monitoring period 2020-2025.

The onset of the monitoring period, spring 2020, was marked as a very dry period. Despite heavy precipitation in mid-June – July, the summer of 2020 was a relatively dry year. On the contrary, summer 2021 was quite wet, as well as winter 2021-2022. A continuous drought, however, marked record breaking levels of precipitation deficit in the summer of 2022. Regular amounts of precipitation where observed in the winter of 2022-2023. In 2023, erratic weather included a drought period with precipitation deficit similar to that of 2020, followed by a record of monthly cumulative rainfall in October and November 2023 and May 2024. The rest of 2024 remained relatively wet with a precipitation deficit comparable to 2021.

3 Intra-annual observations

3.1 Average hydraulic trends

Fig. 3 presents hydraulic data of the Droogtemonitoring project for the period of 2020-2025. As the hydraulic quantities can vary strongly per dyke, it was chosen to average the monitored quantities in the following way. The moisture content data of all ten dyke locations are averaged based on sensor depth (20, 50, 75 and 100-150 cm below soil surface). The piezometer data is presented by means of an average hydraulic head, determined as the mean of the piezometer signals that showed the highest min-max fluctuation per dyke location. In order to observe trends in annual soil drying and wetting, the averaged data of both soil moisture and hydraulic head is normalized to a scale from 0 to 1, corresponding to the annual recorded minimum and maximum value of the respective sensor, herein referred to as the wetness ratio. Additionally, the monthly cumulative rainfall minus evapotranspiration derived from the KNMI weather station of Rotterdam is visualized with a colour bar, that indicates the proportion of the total annual atmospheric wetness reflected in that month. For a structured analysis, the time series on soil moisture content and dyke body hydraulic head are decomposed into three phases:

1) near-saturation: periods of fluctuation within 0.5 -1.0 of wetness ratio.
2) desaturation: periods of declining hydraulic head, initiated from the maximum saturated state towards the minimum state.
3) re-saturation: transitional period between the above phases.

Looking at the 5 years of data, annual min-max fluctuations corresponding to summer drought and winter wetness are clearly recognisable. Additionally, the classification of annual atmospheric wettest and dryest months are indicative of fluctuations in hydraulic responses. The onset period of re-saturation is typically observed in September and October. After re-saturation, the hydraulic head wetness ratio fluctuates within about 0.5 – 1.0 with dynamic responses to individual rainfall events and declines in periodic absence of rainfall.

De-saturation of the dyke body initiates early in the year after the wettest month in the winter season, that is March in the years 2022 and 2024, and February in 2021. Notably, the onset of the de-saturation phase is less straightforwardly defined for the year 2023. The absence of rainfall after January resulted in a relatively strong decline in the yearly wetness ratio of the hydraulic head. This trend is somehow reversed by precipitation in March, as reflected by the shallow moisture content sensors (20-75 cm), which indicate values close to their annual maximum. Only the deeper moisture content sensors at 100 cm and beyond indicate a continuous de-saturation

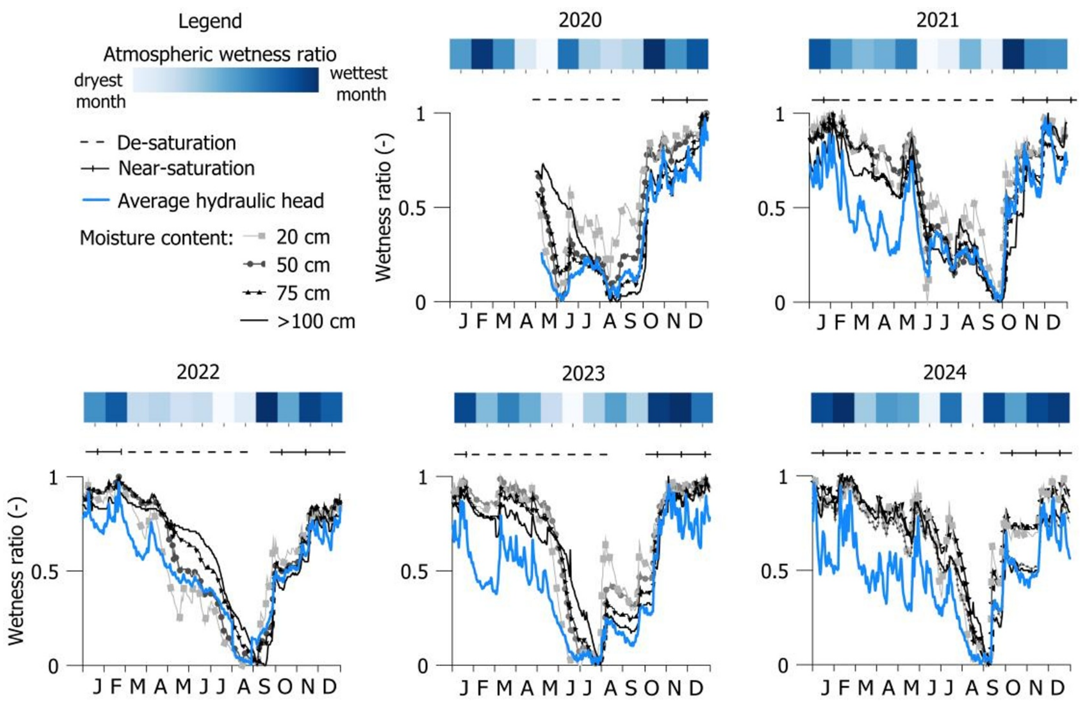

Fig. 3. Annual trends in moisture content and hydraulic head alongside monthly atmospheric wetness.

trend similar to that of the hydraulic head. This marks a response that is also observed in the summer periods of 2020, when shallow sensors dynamically respond to mid-summer rainfall events whilst the deeper moisture content sensors continuously decline. Also in the summer of 2022, moisture content sensors at 50 cm and below barely reflected the rainfall events in May, June and July, indicating the limited depth response to precipitation events, even those with quantities larger than 20 mm/day. This response seems to be correlated with the intensity of drought as reflected by the annual level of precipitation deficit presented (Fig. 2B).

3.2 Case study: Hydromechanical trends

To gain information on the response of atmospheric-driven hydraulic fluctuations over depth, data from the case study is analysed. Fig. 4 presents the extensometer data, including monthly atmospheric wetness, for the year 2024. The data is presented in terms of vertical displacement, z in mm, for each layer derived by subtracting the extensometer signals at the top and bottom interfaces of each layer. To analyse yearly trends, layer deformations are set to 0 at the 1st of January 2024. Positive and negative displacements respectively indicate an increase and decrease of the layer thickness relative to the reference date. Fig. 4B and Fig. 4C present the deformations of the dyke body (D.B.) of the two sections. The deformations of the foundation layers are plotted in Fig. 4D. Additionally, data of each section is plotted along its corresponding piezometer or water pressure sensor.

As the year 2024 was characterized by relatively wet atmospheric conditions, the overall magnitude of layer deformation is limited. However, each signal, including that of the foundation layers, shows a deformation pattern coherent with that of the dyke body hydraulic head and, as discussed in previous paragraph, monthly atmospheric wetness. Surficial layer displacements strongly mimic hydraulic head variations, reflecting dynamic responses to rainfall events. The largest changes in layers thickness, Δz, in the order of 1 to -6 mm, are observed in the peaty dyke body, followed by the clayey dyke body layer with Δz in the order of 1 to -2 mm (Fig. 4B). The decay in magnitude of layer deformation over depth is in line with what can be expected for soil stiffness, therefore, as seen in Fig. 4D, the clayey foundation layer shows a more dynamic response than that of the overlaying sandy clay. Looking at the response to the two drought episodes in June and August, layer compression can be recognized with a delayed response over depth, which is especially appreciated at the base layer.

Comparing the dyke body layer deformations of the two sections with different stratigraphy (Fig. 4B and Fig. 4C), pronounced differences in magnitude can be observed. Though the clayey dyke body layer (from -5 to -6 NAP m, Fig. 1) should be fairly similar for the two sections, the difference in layer deformation suggests a mechanical response to hydraulic variations that is 2-3 times stiffer compared to that mid-slope. This finding seems to correspond to the reconstruction and compaction activities in 2012 that were focused on this dyke section.

Finally, it is observed that over the year, layer displacements of the anthropogenic clay (Fig. 4C) and foundation layers (Fig. 4D) are not fully reversed. This might suggest a possible annual settlement trend as a result of creep, which is commonly observed for these soft soil deposits. However, a longer monitoring period is required to substantiate this conclusion.

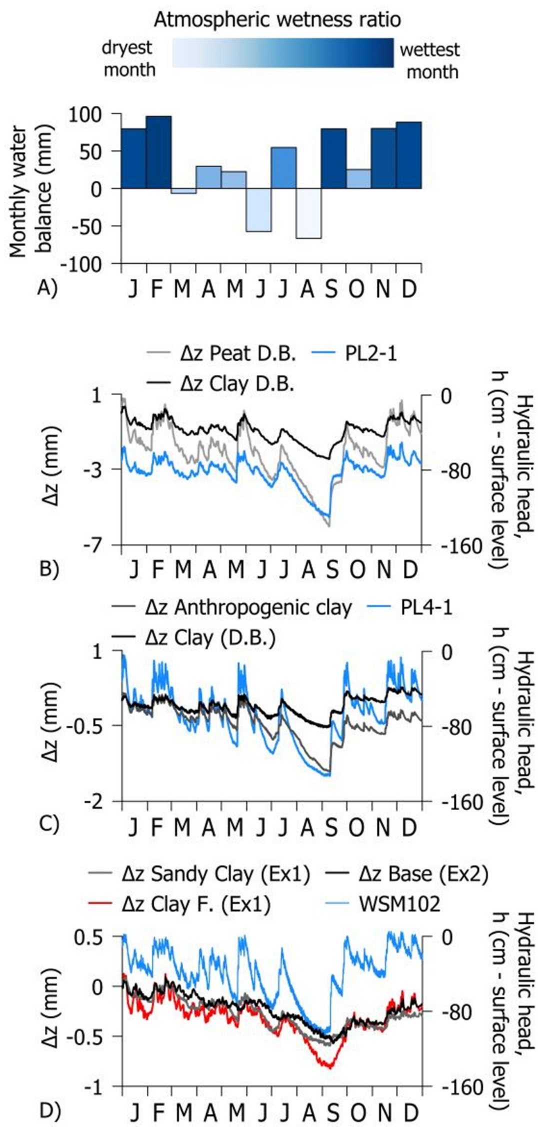

Fig. 4. Data of the year 2024 at the Hennipslootkade. A) Atmospheric cumulative precipitation. B) Dyke body layer displacements Ex1 (Mid-dyke). C) Dyke body layer displacements Ex2 (toe). D) Foundation layers.

4 Inter-annual observations

4.1 Drought events

From a physical viewpoint, weather extremes such as the drought record of 2022 potentially impact soil behaviour over sequential years. To study possible inter-annual effects, Fig. 5A presents the full time series of the average hydraulic head of the ten monitored dykes in terms of wetness ratio over the full time series, which indicates the severity of the 2022 drought event.

As can also be inferred from the annual data presented in Fig. 3, the average level in terms of wetness ratio remained relatively low in the winter of 2022-2023 as a consequence of the high precipitation deficit in summer. Nonetheless, in the years 2023 and 2024, the response pattern of the hydraulic head does not seem to deviate from that of the atmospheric conditions. This is concluded by comparing the yearly minima in hydraulic head with the annual levels of precipitation deficit, presented in Fig. 2B, for which it can be seen that the response in 2023 was similar to that of 2020, as well as 2021 and 2024.

The signal of Fig. 5A is obtained from averaging the responses of multiple dyke sections, whilst the case study allows looking closer into the response of individual soil layers. Therefore, Fig. 5B and Fig. 5C present the time series of PL4-1 (clay) and PL2-1 (peat) respectively, both in terms of wetness ratio and hydraulic head position with respect to surface level. From Fig. 5B it can be seen that the response of PL4-1 resembles strongly that of the average hydraulic head, although typically showing stronger annual fluctuations in terms of wetness ratio. Likewise the average hydraulic head, the multi-year response of PL4-1 shows a resemblance with what is expected from the atmospheric conditions as described by the annual precipitation deficit (Fig. 2). However, for PL2-1 (Fig. 5C), positioned in the peaty layer, it can be observed that the response upon atmospheric drought in 2023 was similar to 2022 despite the difference in drought intensity. Additionally, the hydraulic head in near-saturation phases of both 2022-2023 and 2023-2024 remained lower compared to previous years, and is only re-established at the end of 2024. These observations suggest a stronger sensitivity of the peaty layer to soil storage capacity variations due to the extreme drought event. As a result, the precipitation deficit is less representative for the soil hydromechanical response afterwards. As an alternative indicator, a detrended precipitation deficit is presented in Fig. 6. Instead of working with an annual reset at the onset of growth season, this is a continuous precipitation deficit, determined over the time-span of multiple years, that is detrended based on the annual average trend line. Through the fitted trend line, the inter-annual impact of an extreme event relative to the considered time period is better recognised.

4.2 Rainfall events

Finally, the potential long-term (inter-annual) impact of rainfall records is investigated. Time-series of both PL4-1 and average hydraulic head (Fig. 5A and Fig.5B) reflect responses to the cumulative rainfall record in October and November 2023. For a duration similar to that of the number of sequential days of rainfall, the hydraulic head remained close to its maximum recorded level. For PL4-1, this is about 10 cm higher compared to previous winters. However, despite the wetness record, de-saturation of the dyke body hydraulic head initiates soon afterwards, which marks only a temporary persistence of the precipitation record.

To further investigate the seemingly temporary response to rainfall events, Fig. 7 provides a closer observation to the hydromechanical data of the Hennipslootkade for the time period of April to November 2024. In response to episodic rainy conditions, marked in grey, high elevated levels of hydraulic head and consequential soil heave are maintained for a timespan of approximately 1 to 2 weeks, which corresponds to the duration of the event. In dry periods and under scattered and low intense precipitation the hydraulic head declines fast, followed by a similar response in the extensometers.

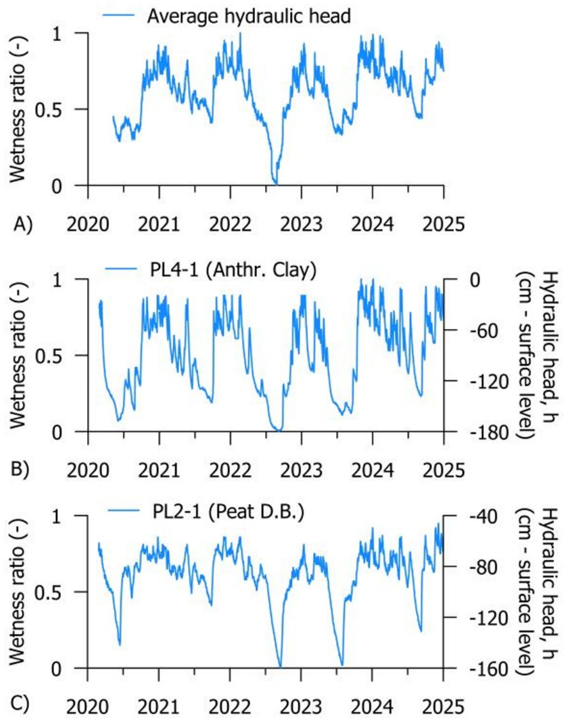

Fig. 5. Hydraulic head time series of A) Average of 10 monitored regional dykes. B) Hennipslootkade, toe. C) Hennipslootkade, mid-dyke.

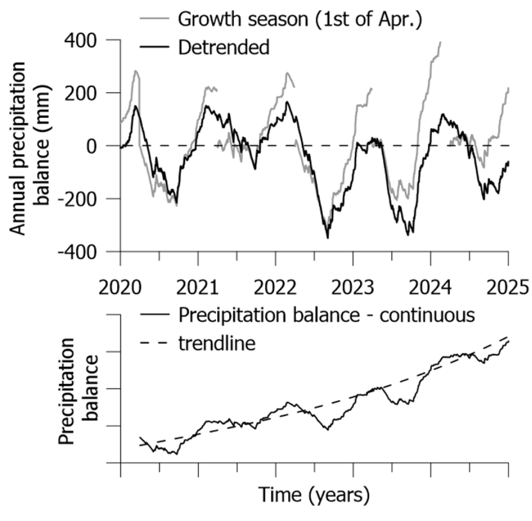

Fig. 6. Detrended annual precipitation balance and continuous precipitation deficit according to growth season.

The sensitivity of the hydromechanical response to rainfall intensity declines as de-saturation continues. Consequently, rainfall events in August seem to have completely smoothened in the unsaturated zone. After re-saturation, also rainfall events with low intensity recur in the hydromechanical response, although the response impact is proportional to the cumulative intensity of the clustered event. This feature is also highlighted by comparing the hydromechanical response to the rainfall events in May and June. The impact of an extreme precipitation event at the beginning of June (>20 mm/day) is less pronounced compared to the previous cluster of less intense, but longer sequence of daily precipitation. From the extensometer signal of the dyke body clay layer it can be inferred that any dynamic responses to daily rainfall events are further smoothened over depth, emphasizing the coherence with clustered precipitation events with duration close to 1 to 2 weeks rather than individual extreme events.

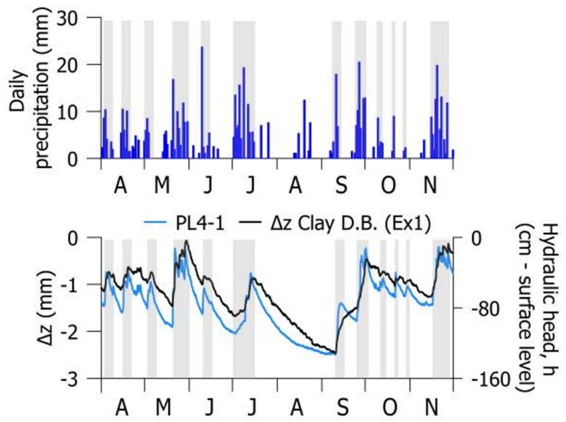

Fig. 7. Hydromechanical data alongside local rainfall events at the Hennipslootkade for time period April - November 2024.

5 Conclusions

To understand how atmospheric conditions impact the hydromechanical in-situ state of soft soil geo-structures, multiple-year monitoring data was analysed to infer typical yearly (intra-annual) variations and potential long-term (inter-annual) variations. Intra-annual analysis indicated the coherence between monthly atmospheric wetness conditions and the hydromechanical response, in which the main annual wetting (winter) and drying (summer) conditions are dominant. Data of the case study showed a decay and delay of this response over depth, including foundation layers. Multi-day periods of rainfall, with a relevant timespan of 1-2 weeks, drive temporary hydromechanical changes. Finally, data analysis highlights the impact of drought periods and the potential long-lasting effect of prolonged drought to climate-sensitive organic soft soil layers.

Although this work focusses on the climatic top boundary, the observed atmospheric-driven hydro-mechanical response is to be contextualized with all relevant boundary conditions, as achieved by geotechnical modelling. For the simulation of multiple years climatic data, it could be considered to adopt clustered atmospheric events to reduce dynamics introduced by the atmospheric boundary. Additionally, the results suggest that it might be less important to strictly simulate the more dynamic soil response at shallow depth (20 – 50 cm), as it was observed that the deeper moisture content sensors (>100 cm) better reflect the main annual de-saturation and re-saturation trends relevant for the geotechnical behaviour of dyke body and foundation layers.

With respect to atmospheric indicators, it could be considered to adopt a continuous formulation of the atmospheric water balance as proposed in this paper, to better reflect potential inter-annual impact of drought events on climate-sensitive layers, and better capture the onset of annual de-saturation. Considering the expected shifts in atmospheric water balance due to global warming, the formulation of a representative drought indicator becomes increasingly relevant. Continuation of field monitoring of various dyke typologies is crucial to provide further information on the long-term response of soft-soil dyke structures, which supports the improvement of geotechnical assessments and the design of effective dyke management activities under future climatic conditions.

This publication is part of the project Sustainable Dykes TWM.BL.2019.010 of the research programme Top Sector Water and Maritime: Blue route, financed by the Dutch Research Council (NWO). The authors gratefully acknowledge the financial support of STOWA, the Dutch foundation for research on regional dykes, and the water boards of Rijnland, Delfland and Schieland and Krimpenerwaard.

References

[1]. E.J. Den Haan, G.A.M. Kruse. Characterisation and engineering properties of natural soils. **3**, 2101–2133 (2007).

[2]. H.F. Zhao, C. Jommi. Can. Geotech. J. **59**, 1712–1727 (2022).

[3]. S. Van Baars. Géotechnique **55**, 319–323 (2005).

[4]. B. van der Kolk, M. van der Krogt, T. Stoeltjesdijk, M. Hijma. *Oorzakelijk onderzoek kade afschuiving Reeuwijk*, Deltares (2023).

[5]. B. Strijker. *Impact van de natte winter 2023–2024 op boezemkaden*, STOWA (2025).

[6]. G. Elia, F. Cotecchia, G. Pedone, J. Vaunat, P.J. Vardon, C. Pereira, ... P. Osinski. *Q. J. Eng. Geol. Hydrogeol.* **50**, 249–270 (2017).

[7]. I. de Wolf, C. Jommi. *7th Int. Conf. on Geotechnical and Geophysical Site Characterization. ISC'7 2024*, 580–586 (2024).

[8]. K. van der Wiel, J. Beersma, H. van den Brink, F. Krikken, F. Selten, C. Severijns, ... R. van Dorland. *Earth's Future* **12**, e2023EF003983 (2024).

[9]. B. Strijker, T.J. Heimovaara, S.N. Jonkman, M. Kok. *Water Resour. Res.* **60**, e2023WR036046 (2024).

[10]. H.A.R. De Bruin, W.N. Lablans. *Hydrol. Process.* **12**, 1053–1062 (1998).