On the seasonality of soil strength in CPTu investigation

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Abstract. Increasing extremes in atmospheric drought associated with climate change raise growing concerns on the potential impact of climatic actions on the geotechnical stability of regional dykes in the Netherlands. Accurate quantification of seasonal soil strength variations under in-situ conditions is essential to assess this impact. Cone penetration testing (CPTu) is widely adopted to assess material strength, however, the influence of seasonality on CPTu data is largely overlooked in current practice. This contribution presents the results of CPTu investigations repeated at one regional dyke location under variable atmospheric conditions, ranging from winter wetness to severe summer drought. The observed differences in resistance and pore pressure between the CPTu data collected over different seasons highlight the impact of drought on soil strength. It is shown that conventional interpretation tool for saturated soils cannot be used straightforwardly to analyse the data. In the variably saturated zone, clear derivation of strength is hindered by current knowledge gaps. Possible interpretation of CPTu data for constant water content shear strength is discussed for both the saturated and the unsaturated zones in view of dyke stability assessment, with the aid of expected soil physical behaviour and parallel data from in situ hydro-mechanical monitoring.

1 Introduction

Changing climatic conditions are increasingly threatening the structural stability and integrity of flood defences in the Netherlands, where regional dykes form a significant portion of the flood defence infrastructure. These geo-structures are commonly limited in height and constructed on, or composed of, soft Holocene soil deposits. Given the low effective stresses inherent to soft organic soils, atmospheric-driven changes in groundwater conditions can lead to relatively large variations in the stress state, making regional dykes extremely sensitive to climatic variability. Increasingly frequent weather extremes associated with climate change exacerbate the need to improve the assessment of climate-related impact on stability. To this scope, extensive monitoring and site investigation programmes have been initiated recently in the Netherlands, with the aim to improve maintenance practices and safety of soft soil regional dykes [1-3].

Stability assessment requires the characterisation of reliable soil strength properties across the range of in-situ conditions to which these structures are subjected. Cone penetration testing with pore pressure measurement (CPTu) is one of the most widely used investigation techniques in the Netherlands to infer the shear strength, which is directly derived from the field data and applied in soil calculations. Current interpretation frameworks often rely on simplified assumptions derived from international literature, developed predominantly for mineral soils, which may not adequately capture the behaviour of the soft organic soils typical of Dutch regional dykes [4].

Moreover, the potential influence of seasonal soil state variability on CPTu measurements has received little attention so far [5]. This knowledge gap hinders proper assessment of the potential impact of climate stresses on the available soil strength over time.

This contribution investigates the limitations in CPTu interpretation for soft Holocene deposits under variable climatic conditions, by means of a dedicated field investigation programme. Repeated CPTu tests were performed at the same regional dyke section, called the MT-Polder, across different periods of the year, encompassing conditions of atmospheric wetness and prolonged drought. CPTu data are analysed and interpreted to estimate the impact of seasonality on the constant water content shear strength in the soft soil dyke body and foundation layers. Recommendations for further research are given to allow better quantification of seasonally variable soil strength, for the evaluation of climate-induced variations of dyke stability.

2 Site monitoring programme

2.1 Description of the site

Monitoring data are collected at the MT-Polder, located near Reeuwijk in the Netherlands. The area is characterised as a low-lying polder area, that originates from land reclamation in the 19th century. Fig. 1 illustrates the dyke cross-section and includes the stratigraphy, which predominantly consists of peat and (strongly) organic clay. The Pleistocene sand aquifer is encountered at a depth of approximately -11 NAP m.

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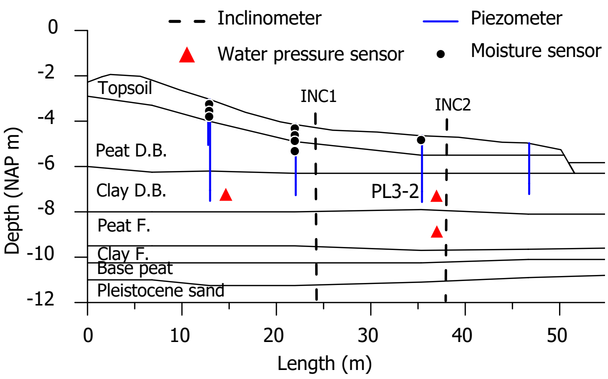

Fig. 1. Dyke cross-section with monitoring at the MT-Polder.

The monitoring instrumentation, operating since 2020, which consists of moisture content sensors, piezometers, water pressure sensors and inclinometers is also depicted in the figure [1, 3].

2.2 CPTu investigations

Three rounds of CPTu tests have been repeated under variable atmospheric conditions at the dyke crest, mid-slope and toe of the dyke, within the zones indicated in Fig. 2. Tests have been performed according to NEN-EN-ISO-22476-1 class 1 norm. The surface area of the applied cone is 10 cm^2. Penetration is performed at a rate of 2 cm/s, with readings at every 2 cm over depth.

With reference to the lowest and highest recorded positions of the ground water table, as inferred from the monitoring data in the period 2020 until 2025 (Fig. 2), the conditions upon CPTu investigations in March 2023 are representative for annual maximum dyke saturation, herein also referred to as winter conditions. CPTu tests in July 2025 were conducted under average annual drought conditions, corresponding to a precipitation deficit (PD) [2] of approximately 180 mm. Tests performed late August 2025 were conducted within a period of prolonged drought, corresponding to an annual PD of approximately 300 mm, among the top 5% driest atmospheric conditions recorded since 1901.

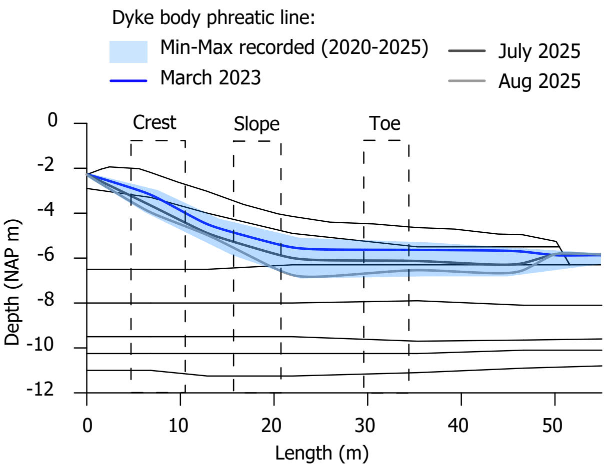

Fig. 2. Variations of the hydraulic head in the dyke body, along with the zones of repetitive CPTu tests.

3 Field data

3.1 Cone resistance (q_c) and sleeve friction (f_s)

The cone resistance, q_c, and sleeve friction, f_s, of the three CPTu investigation rounds are reported in Fig. 3 and Fig. 4, respectively. Most of the variability in q_c and f_s is appreciated in the top first 1.5 to 2 meter, in the sandy topsoil and peaty dyke body layer above the water table of each respective CPTu round. Below the water table, the profiles look fairly similar, with little variations which can be due to the natural heterogeneity of the soil.

The largest difference in q_c is observed between March and July, whilst only subtle differences are apparent between July and August. Comparing q_c with f_s profiles, it is inferred that the cone resistance is consistently higher in drying conditions, whilst a less consistent trend is obtained for the sleeve friction.

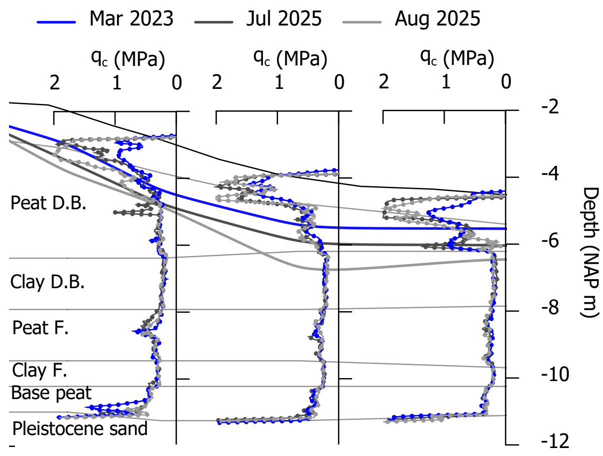

Fig. 3. Cone resistance alongside dyke cross-section for repetitive CPTu investigations.

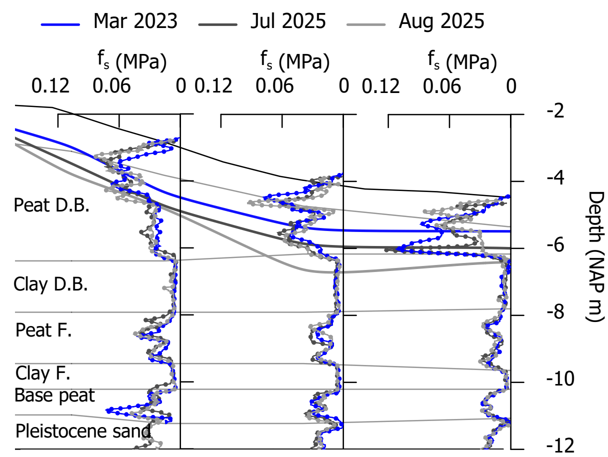

Fig. 4. Sleeve friction alongside dyke cross-section for repetitive CPTu investigations.

3.2 Pore pressure (u_2) and friction ratio (R_f)

The pore pressure profile recorded by the cone along the shaft, u_2, is presented in Fig. 5. Contrarily to q_c and f_s, prominent variations in u_2 are apparent in the Holocene deposits below the water table, while little u_2 is generated in the topsoil above the ground water table.

It can be observed that variations in u_2 are strongly linked with the soil composition, as reflected by the friction ratio, R_f, presented in Fig. 6. Clayey layers show more regular increase in u_2 over depth, whilst pore pressure fluctuates more inside peat layers as a result of higher variability in soil composition and organic matter of the material. The profile of u_2 recorded within the Pleistocene sand is almost constant over time. Unexpectedly, the comparison of u_2 profiles at different times show recorded water pressures that are generally larger in summer (July and August) compared to winter (March).

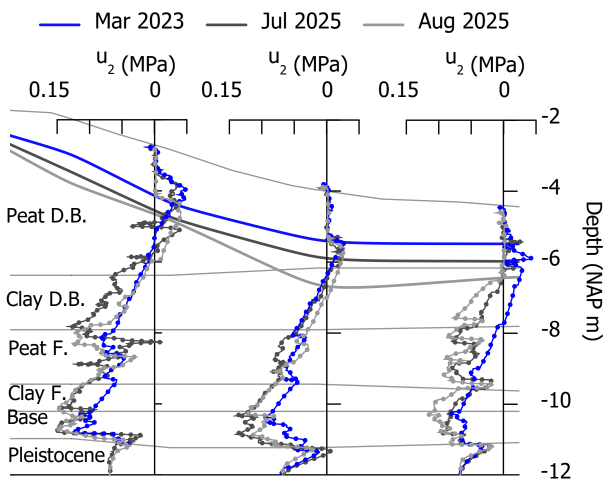

Fig. 5. Pore pressure alongside dyke cross-section for repetitive CPTu investigations.

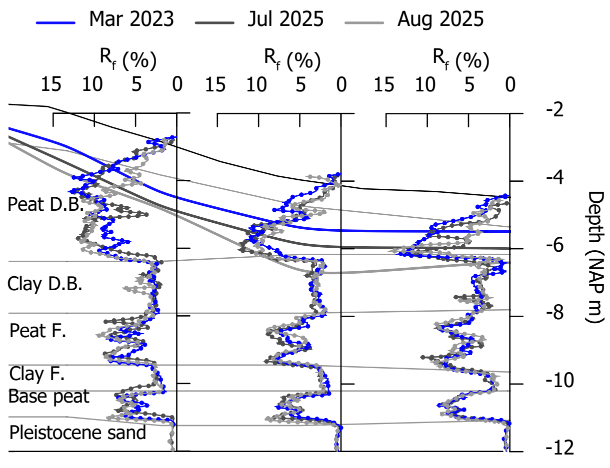

Fig. 6. Friction ratio alongside dyke cross-section for repetitive CPTu investigations.

4 Data analysis

4.1 Theoretical background

The CPTu data are analysed with the aim to infer the impact of seasonal variability on the geotechnical soil response. In the practice, the response of soft clay and peat layers is assumed to be undrained during CPTu tests. Therefore, interpretation and correlations with the soil behaviour, including strength, are referring to undrained conditions.

Two approaches are commonly used to derive the soil undrained shear strength S_u from CPTu data. The first approach uses directly the net cone resistance q_{net} and an empirical correction factor N_{kt}, according to:

$$S_u = \frac{q_t - \sigma_v}{N_{kt}} = \frac{q_{net}}{N_{kt}} . \quad (1)$$

A second approach, currently embedded in the Dutch framework for dyke safety assessments, uses the SHANSEP formulation [6] to account for the influence of soil history and effective stress, via:

$$S_u = S\, OCR^m \sigma_v' . \quad (2)$$

Although linked to the soil friction angle and the compression indexes, S and m are soil-specific parameters, which typically require substantiation from laboratory tests on undisturbed samples, replicating as much as possible the soil conditions on site. However, these conditions are not easily reproducible in the laboratory. When dealing with organic soils, retrieving undisturbed samples can be challenging and laboratory testing can be largely affected by anisotropy and scale effects. This is especially true for organic soils, whose behaviour is largely dominated by the fabric of the organic components at the typically low stress levels in the field [7]. As both approaches for S_u determination have been developed based on experience of mineral soils, the fitting parameters S, m and N_{kt} can show considerable scatter [8]. Moreover, it is worthwhile noting that both approaches are only applicable to derive undrained shear strength for saturated soils. For unsaturated soils, a different stress-strength framework is necessary as, for instance, the one proposed in [3].

Accounting for the role of variable saturation on soil strength requires inclusion of soil properties that are associated with water retention ability and shrinkage behaviour, which again results in thorough advanced laboratory investigations to support parameter calibration. Due to the large range of suction that unsaturated soils can experience in the field, soil structural fabric alteration and cracking are prominent aspects, which are expected to strongly influence the soil response over time [9]. A comprehensive approach, able to reliably exploit CPTu data in the unsaturated zone, has not been fully developed yet [3, 5].

Despite these limitations, current extensive research on interpretation frameworks of CPTu data can offer a useful preliminary tool for identifying relevant soil behavioural trends from the experimental data gathered under variable climatic conditions, which is illustrated in the following section.

4.2 Effective stress profiles

The in-situ vertical effective stress profiles σ_v' estimated at the time of CPTu testing are presented in Fig. 7. The effective stress is estimated everywhere as the difference between the total vertical stress and the pore water pressure. This choice, although debatable for the unsaturated zone from a conceptual viewpoint, has the advantage of giving a simple practical reference for applications in the field. Variations in effective stresses result from atmospheric-driven changes in both the dyke body phreatic line and the Pleistocene sand at the bottom, which shows a seasonal variation in the order of 10 kPa at the crest to 3 kPa at the toe. Changes in the position of the water table and water content of the peaty dyke body go along with a significant reduction in weight. As a result, it can be observed that the vertical effective stress increases over summer in the most surficial layers, whilst a reduction may be expected at larger depth.

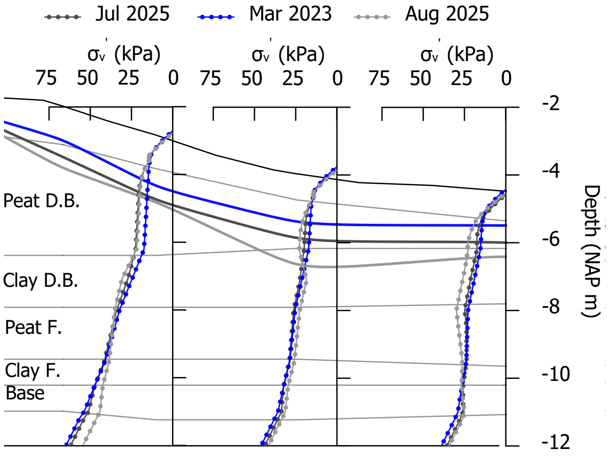

Fig. 7. Effective stress conditions of CPTu investigations.

4.3 Saturated zone - Net cone resistance

To get better insight in the variation of the undrained shear strength in the saturated zone, the net cone resistance q_{net} is presented in Fig. 8. To explore the seasonal shear strength variation in the relevant layers below the water table, the scale of q_{net} is set to the range from 100 to 400 kPa.

Within this range, subtle variations in q_{net} can be recognised, which illustrate, according to Equation (1) and a constant N_{kt} value, both increases and decreases of the undrained shear strength. The trend in q_{net} generally connects well with the estimation of the effective stress conditions at the time of the investigation (Fig. 7). Notably, unfavourable effect of drought conditions on q_{net} are apparent in the slightly reduced net cone resistance at -11 m NAP at the dyke toe, and beyond a depth of approximately -6.5 NAP m at the slope. However, the correlation between effective stress conditions and q_{net} is not strictly consistent for all CPTu data. This is best apparent for the profile at the dyke crest, where, contrarily to what is expected from seasonal effective stress conditions, readings in August indicate a decrease of q_{net} compared to July.

According to the SHANSEP formulation (Equation (2)), the over consolidation ratio, OCR, partly counteracts the effect of decreasing effective stress on the undrained shear strength. Therefore, the next section investigates the CPTu data in the Q_t - B_q soil behavioural framework [10] to detect how the OCR of individual layers varies over time.

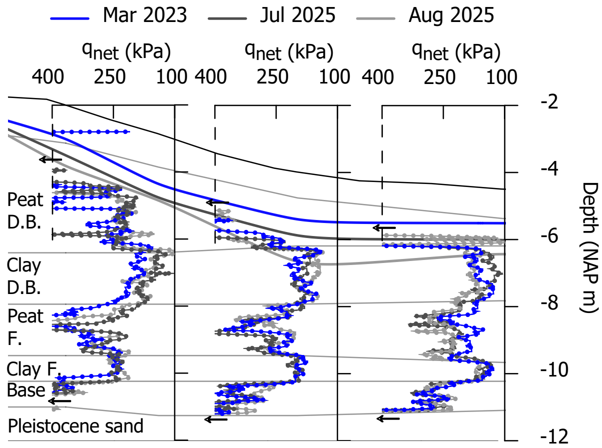

Fig. 8. q_{net} for the various CPTu rounds.

4.4 Observations on soil behaviour

Data of the CPTu rounds are plotted in the soil behaviour chart as normalised net cone resistance Q_t against pore pressure ratio B_q [10]. For the sake of brevity, Fig. 9 presents only the data at the dyke crest and toe.

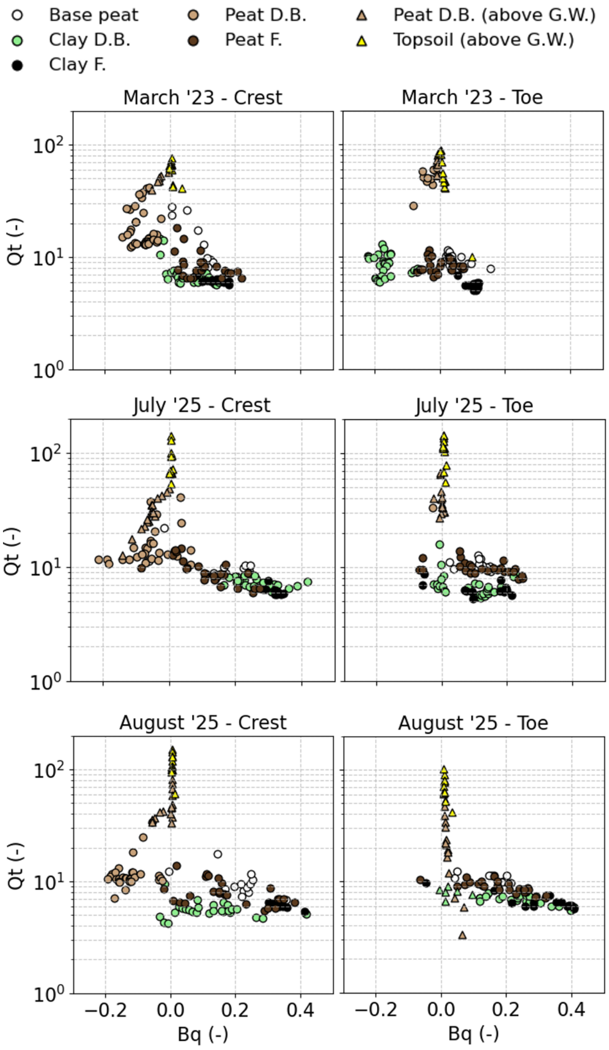

Fig. 9. CPTu data at crest and toe plotted in Q_t - B_q plane.

Comparing the CPTu data from repeated testing in the Q_t - B_q plane, a distinctive behaviour of the peaty and clayey dyke body (D.B.) layers emerges. The data taken in March '23 show negative B_q values in the peaty dyke body layer. According to the common interpretation, this would indicate dilative behaviour which would be justified by an over consolidation history. On average, the values are higher at the crest, though at the toe the effect extends downwards to the clayey dyke body layer.

In Fig. 9, it can be observed that the peaty layer at the toe shifts from negative values in winter to a B_q of approximately zero in July and August, indicating no development of excess pore water pressure upon cone penetration. Similarly to the topsoil, changes in Q_t are observed upon drying, which are discussed in the next section.

Looking at the soil layers that remain fully saturated, a clear shift towards positive B_q values is observed between March and July in both the clay dyke body and the bottom foundation layers, whilst Q_t remains fairly constant. This shift suggests an increasingly contractive soil response at increasing stress and decreasing OCR, with increasing pore pressure generation upon cone penetration (Fig. 5). Notably, the clayey D.B. layer at the toe, which appeared to be over consolidated in March, transitions towards a normally consolidated state upon drawdown of the water table in July. The changing external conditions, going from atmospheric wetness (March) to drought (July, August), seem to promote an increasingly contractive behaviour upon penetration. The transition is already evident at the crest in July, while only appears in August at the toe. The observed transition can be possibly attributed to drought-induced material shrinkage and associated reduction in hydraulic conductivity.

4.5 Strength above the water table

The cone resistance q_c in the upper layers of the dyke, where soils experience a variation in the position of the water table is reported in Fig. 10, together with water content measurements taken at the same time instants.

Between March and June, the moisture content decreases most prominently within the upper 75 cm below surface level, alongside increasing q_c. Upon intensified drought between July and August, moisture content variations become marginal within this depth range. However, further increases in q_c, as apparent at the crest, may be reflective of ongoing build-up of suction stresses at little moisture content variations.

A similar trend in q_c is not equally recognised at the toe. To explain the difference between crest and toe, the datapoints referring to the upper zones plotted in Fig. 9 can be compared with each other. Besides effective stress and OCR, a change in B_q can be associated also with soil fabric changes occurring during desaturation. For the sandy topsoil, which is typically less sensitive to fabric modification, favourable effect on the mechanical strength (Q_t) is observed upon drought. A similar increase in Q_t is observed for the peaty dyke body at the crest, whilst a reduction in Q_t is observed in August 2025 at the dyke toe.

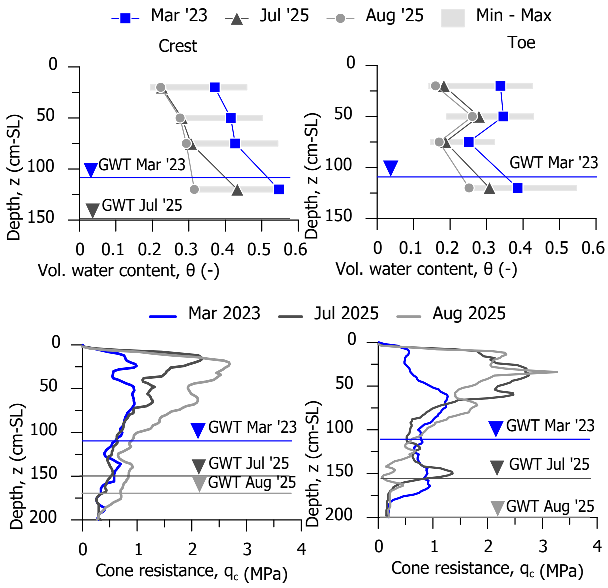

Fig. 10. Soil moisture content and cone resistance recorded over depth (cm below surface level) in the unsaturated zone.

The observed difference in the time dependent Q_t trend suggests that the peat layer at the crest is more protected from fabric changes than the layer at the toe. On the one hand, the overall position of the groundwater table with respect to the recorded min-max position (Fig. 2) can play a role, considering that the hydraulic dropdown at the toe in the year 2025 might be associated to a historic minimum. On the other hand, the peat layer at the toe is more exposed to drying-wetting cycles, which will impact the degree of degradation of the soil fabric [11]. Although the latter tentative explanation is supported by literature knowledge, dedicated laboratory investigation is necessary to improve the understanding of the combined role of loading history and degradation state on these specific soils, and better support the interpretation of seasonal CPTu data.

5 Engineering implications

5.1 Engineering impact

The field measurements and their preliminary analysis highlight that climate-driven variations in water content, soil loading history, pore pressure and effective stress conditions all contribute to variations in soil strength of relevance in the geotechnical stability assessments of regional dykes. However, contrarily to a common belief and to practical engineering assumptions, the results of repeated CPTu investigations do not strictly indicate a steady increase in the soil strength and dyke resistance with drought. The discrepancy between the actual and the modelled in-situ soil behaviour can have large practical implications.

An exemplary case is provided by a dyke failure that occurred in the same polder area as the MT-Polder in the summer of 2021 [8]. Failure occurred in the absence of identifiable external loading triggers, which raised concerns regarding the potential loss of dyke resistance due to seasonal variability, or long-term processes such as soil deformations and material degradation.

Such mechanisms are not explicitly included in safety assessments for dyke maintenance, given that the unsaturated part of the system is assumed to increase its strength over drought, and that the soft soil Holocene deposits, which remain in saturated state, are expected to be hardly affected by climatic stresses.

Of the two components, the variably saturated zone got more attention in the analysis and assessment of seasonal driven time-dependent variations in soil state. Although the favourable impact of variable saturated conditions on the mechanical strength is known, concerns exist regarding the potential formation of desiccation cracks and the associated reduction in strength. As a result, highly conservative assumptions on soil strength are often adopted in the practice by fully neglecting the contribution of the unsaturated zone to dyke stability. While this approach is aimed to ensure safety, it hinders reliable assessment of the actual stress conditions and prevents proper understanding of the mechanisms controlling dyke stability and their dependence on seasonal fluctuations.

A thorough investigation on the Reeuwijk failure event, after it occurred, indicated a relatively deep slip surface that extended over the full depth of Holocene deposits as indicated in Fig. 11, which emphasises the importance of characterising adequately the shear strength in the saturated zone. This also highlights that, although the impact of seasonality on strength may appear limited in absolute terms, it can be dramatically significant for stability, given the low effective stress characterising the soft soil foundation layers.

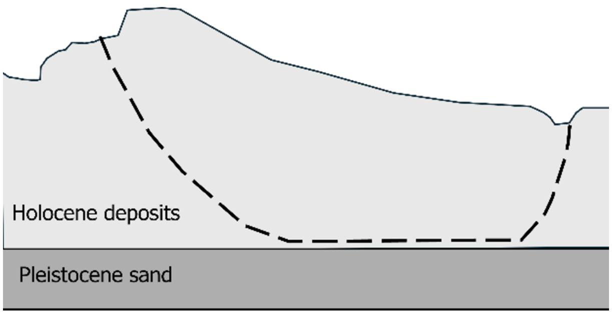

Fig. 11. Illustration of the possible failure plane of the Reeuwijk dyke, after [8].

In the following, available data from monitoring at the MT-Polder are combined with CPTu results to start analysing more in depth the combined hydro-mechanical pre-failure behaviour, to better identify those processes that might contribute eventually to dyke failure, in an attempt to reduce the knowledge gap on currently unexpected incidents.

5.2 Unsaturated zone strength

Following the seasonal variation in q_c (Fig. 3) and the observations in the Q_t - B_q plane, strength increase upon drought seems to be applicable in the unsaturated zone for sandy silty soils, which are less susceptible to fabric changes. For the peaty material in the unsaturated zone, drought-induced fabric changes may have negative consequences to mechanical strength. Differences were observed between crest and toe, which suggests that considering the soil loading and degradation history may be relevant. Despite the scatter, an overall favourable resistance increase upon increasingly unsaturated conditions seems to be applicable.

In Fig. 12 the CPTu cone resistance is plotted against monitored water content. The data can be compared to those from a former experimental investigation [3], in which the undrained shear strength in the unsaturated zone was quantified by means of constant water content triaxial tests in the laboratory and compared with the values found from repeated CPTu investigations. With a variability in cone resistance in the order of 1 to 5 MPa, similar to the one observed on the MT-polder site and reported in Fig. 12, the seasonal variation in undrained shear strength was found to be in the range 50 – 200 kPa. The data emphasise that S_u in the unsaturated zone is consistently significantly higher than the conservative value of 0 adopted in the practice, and that the summer values are consistently higher than those in winter, despite possible cracking and degradation phenomena. In other words, even if degradation occurred, suction is still the prevailing positive contribution to the strength.

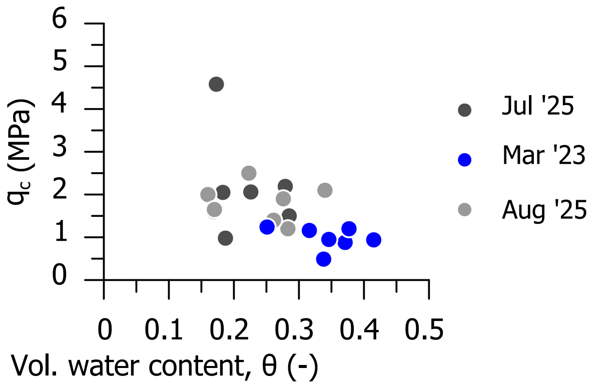

Fig. 12. Volumetric water content versus cone resistance in the unsaturated zone.

5.3 Kinematic behaviour upon drought

The previous observations do not explain why failure may occur unexpectedly in summer. On the contrary, they identify ignoring unsaturated strength as a contributing factor to the excessive conservatism adopted in the practice. To provide more insight into the seasonal impacts, the CPTu data is analysed once more along with findings of the hydromechanical monitoring data (Fig. 1).

Observations interpreted within the Q_t - B_q soil behaviour framework indicate that, during the 2025 drought event, the soft soil deposits exhibited a shift towards more contractive behaviour and higher development of pore pressure (higher u_2 values), likely attributable to soil shrinkage. At the site, the monitoring instrumentation did not include extensometers, therefore, the magnitude and rate of soil shrinkage could not be quantified from vertical displacements directly. However, horizontal deformations from inclinometers measurements can provide as well useful information on the deformational response of the dyke to the cyclic climate loads.

Fig. 13 presents the cumulative displacement at the slope of the MT-Polder (INC-1, Fig. 1) for the year 2025 together with the hydraulic head variation of piezometer PL3-2 (Fig. 1). On top of the figure, the drought impact is presented by means of the precipitation balance, reset to 0 on the first of January 2025 and negative in case of deficit.

Until July 2025, limited hydromechanical variations are observed upon drying, followed by rapid changes. At the same time, as inferred from Fig. 9, the soil above the ground water table stopped developing excess pore water pressure upon cone penetration. Besides desaturation, which could explain low pore pressure, the acceleration in the hydraulic head loss, observed from piezometer PL3-2 readings, might have been facilitated by fabric modifications induced by drying, which increase the overall hydraulic conductivity [11].

Following the sharp decrease in pore pressure recorded at the middle of the dyke, inclinometer 1 indicated significant outward horizontal slope movements in the order of 3 cm in the period from July to September. This deformation mode is accompanied by changes in the confining horizontal stresses, which, in turn, is likely to affect the cone penetration resistance. A reduction in the net cone resistance at the crest and slope, as indicated by the CPTu data in August, might be a consequence of a reduction in the lateral confining stress, which neither SHANSEP nor direct estimation of S_u from q_{net} are able to account for.

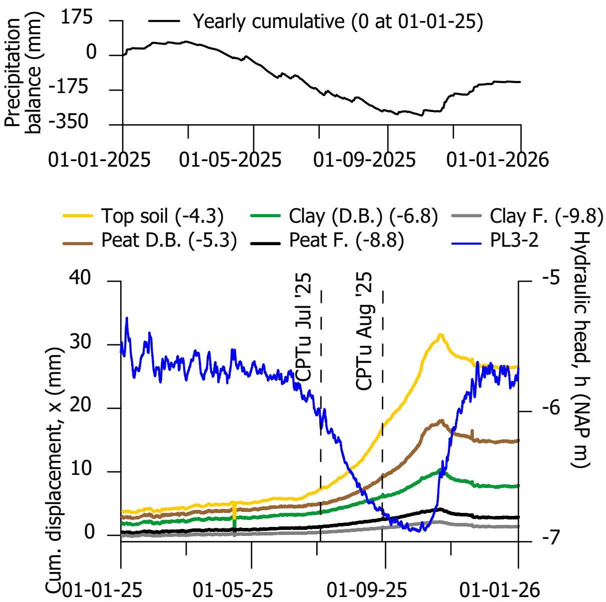

Fig. 13. Horizontal displacement of various soil layers (depth indicated in NAP m) alongside hydraulic head variation of piezometer PL3-2 (Fig. 1) and atmospheric precipitation deficit.

The inclinometer at the toe (INC-2, Fig. 1) recorded relatively limited displacements, up to 6 mm in total, within the same period. As discussed in sections 4.3 and 4.4, in the absence of relevant lateral deformation seasonal variations in q_{net} at the toe could be interpreted as the result of the estimated vertical stress changes and trend in over consolidation ratio of the layers.

Interestingly, observations in the Q_t - B_q plane at the crest had already indicated an increasingly contractive behaviour of the foundation layers at the beginning of July, differently from the response obtained for the dyke toe. This suggests that changes in the soil response according to the Q_t - B_q framework may be early indicators of deformation mechanisms occurring in the field.

6 Conclusion

This study was motivated by the occurrence of few failures of regional dykes in the Netherlands in the recent years, which occurred in summer and without a clear triggering source. Repeated CPTu investigations conducted on a paradigmatic regional dyke confirm that the water defence system is sensitive to climate impact, including prolonged drought periods. Monitoring water pressure and deformation helps in interpreting seasonal CPTu data variations and reveal the role played by various aspects of the coupled hydro-mechanical response on the mobilised shear strength.

The collected data confirm that, overall, drought has a favourable effect on shear strength in the upper variably saturated soil layers. However, the deep failure planes observed in past failure events, indicate that a relatively large contribution to the global dyke stability comes from the lower saturated zone. Besides the well-known effect of suction on the upper soil layers, and the possible degradation processes affecting the soil fabric upon drought and cyclic drying-wetting, this study highlights that more subtle variations may occur over depth, which might be revealed by looking at CPTu data in the Robertson Q_t - B_q plane.

Among the observations found in this investigation, possible decrease of shear strength during summer in the saturated layers, despite increasing effective stress, is worthwhile noting. The analysis of CPTu data revealed that upon drought, soft Holocene layers in the foundation tend to become more contractive and develop higher pore pressure, in turn decreasing the shear strength that can be mobilised. Data suggest that the unexpected response may be a consequence of shrinking, which occurs during summer at increasing water deficit. The tendency is anticipated by the Q_t - B_q combination of CPTu data, which shows a progressive shift from dilative to contractive at increasing water deficit. Although the changes are small in absolute terms, they may be relevant on the stability of the system given the very small total stresses that characterise these structures.

Additional monitoring data, able to track pore pressures and deformations, also revealed that changes in the lateral confining stress, coming from non-uniform hydraulic head decrease and differential horizontal displacement in the dyke body might influence the mobilised strength

The study highlights the limitations of both the SHANSEP framework and the $q_{net} - Nkt$ correlations in evaluating reliable shear strength estimate when analysing the impact of cyclic water balance. The data show that multiple hydro-mechanical mechanisms can

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interact with each other under cyclically variable water deficit, and call for further research aimed at the development of a suitable comprehensive theoretical framework and modelling tool to better assess dyke stability in view of increasing climatic pressure.

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