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DOI
10.1201/9781003308829-132

Publication date
2022

Document Version
Final published version

Published in
Cone Penetration Testing 2022 - Proceedings of the 5th International Symposium on Cone Penetration Testing, CPT 2022

Citation (APA)
de Gast, T., Gavin, K. G., Notenboom, P. D., Abraimi, R., & Reale, C. (2022). CPT based liquefaction potential of flood defences in The Netherlands. In G. Gottardi, & L. Tonni (Eds.), *Cone Penetration Testing 2022 - Proceedings of the 5th International Symposium on Cone Penetration Testing, CPT 2022* (pp. 889-893). CRC Press / Balkema - Taylor & Francis Group. https://doi.org/10.1201/9781003308829-132

Cone Penetration Testing 2022 – Gottardi & Tonni (eds)

CPT based liquefaction potential of flood defences in The Netherlands

T. de Gast & K.G. Gavin
Section of Geo-Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

P.D. Notenboom & R. Abraimi
Afdeling Kennis & Advies, Waterschap Hollandse Delta, Ridderkerk, The Netherlands

C. Reale
Department of Architecture & Civil Engineering, Centre for Infrastructure, Geotechnical and Water Engineering Research (IGWE), University of Bath, Bath, UK

ABSTRACT: The paper describes a study on the liquefaction potential of flood defences along the rivers running through the delta area of the Netherlands. The study concentrates on an area south of Rotterdam. The dykes used as primary flood defences protect an urban, rural, and industrial area of 102,400 ha. In this paper the data from more than 4200 Cone Penetration Tests, CPT traces are used to assess more than 200 km of dykes. The pore pressure, u2 data is analysed, then used to separate the material response into contractive and dilative zones. Using the separation of liquefaction susceptible soils, and geometry of the riverbed a regional hazard map is generated. The choices for the data visualisation and their effect on the generated map are discussed and presented. The final liquefaction susceptibility map is used by the water governing authority Waterschap Hollandse Delta as a decision-making tool to improve the efficacy of liquefaction hazard assessment such as the location and return period of bathymetry measurements, and the scale of site- and laboratory investigation.

1 INTRODUCTION

In the Dutch delta, the majority of rural, industrial, and residential land are founded below mean sea level. These areas are reliant on flood defences for everyday protection. In 1953 a major flood following a heavy storm led to some of these dykes failing, which in turn led to large scale flood inundation and loss of life. Since 1953 extensive flood defences along the delta have reduced the risk of coastline flooding significantly. Dykes in the Netherlands are separated into two general types i) primary dykes which protect along the coast and rivers that have large fluctuations in water level during normal operation; and ii) regional dykes, which surround polder-systems where water levels are artificially maintained with little to no fluctuation. The responsibility to protect against inundation in the Netherlands has been given to separate water governing authorities. The water governing authority Waterschap Hollandse Delta (WSHD) are responsible for the safety of the primary and regional dykes around the Islands in the province of South Holland. There are approximately 200 km of primary dykes preventing the local area from flooding. These dykes need to be assessed frequently, considering several different failure mechanisms and their safety needs to be evaluated and in turn reported to the national government. As part of their most recent assessment, WSHD conducted a large site-investigation campaign consisting of more than 5,000 (or exactly 5,137) Cone Penetration Tests (CPT), 800 boreholes and substantial laboratory tests on the soft deltaic soils. This study utilises this dataset to check for the potential of sand liquefaction beneath the Dykes.

Static liquefaction can occur when loose saturated cohesion less soils are loaded rapidly, for example due to slope over-steepening. Erosion of rivers in the governance area of WSHD affects the slopes of the river channel. This erosion can lead to underwater slope instability potentially leading to a static liquefaction type failure. The current assessment criteria (Rijkswaterstaat 2019) proposes a stepwise approach, where high hazard locations are identified based on their geometry, informed by both the bathymetry of the river basin and the physical geometry of the dyke. High hazard locations are then subjected to more detailed analysis. This study proposes to add to the geometrical data used to pre-screen high hazard locations by using the material behaviour chart (Robertson 2016) to identify underlying soil susceptible to liquefaction in the WSHD area.

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2 GEOLOGY OF AREA

The area of investigation lies in the Rhine-Meuse delta which discharges to the North Sea. The river basin consists of silty clay and organic (clay) deposited on top of a Pleistocene sand layer typically located at depths from Dutch Ordnance Datum Level (NAP), NAP -15 m to NAP -20 m depth (≈15 to 20m below ground level in this low-lying coastal region). The clay and organic soil layers are intersected by several meandering streams forming channel belts, these are mapped by (Cohen, et al. 2012). Currently the rivers are 'locked' in place, meaning that old river channels locations have been fixed in location by engineering works. Dykes have been built to prevent flooding which can change the natural flow path of a river whilst additionally the riverbed is frequently dredged to allow for the safe operation of inland ships serving the Port of Rotterdam and maintain the discharge capacity of the river.

3 METHODOLOGY

Loose silts and fine sands will tend to contract when loaded. During regular static loading where loads are applied slowly (e.g. during construction of a building or dyke) pore pressures dissipate, and settlement occurs. However, if the rate of loading (or unloading) is high, e.g. during erosion, excess pore pressures develop and may lead to liquefaction and sudden large failure e.g. as shown in Figure 1. In dense sands this is not an issue as the particles want to dilate under loading, increasing the voids between particles and consequently the volume for water to occupy. One of the indicators of contractive/dilative behaviour is a sands relative density.

In an extensive site-investigation campaign WSHD has performed, 2 CPTs per 100 m length on both the top of the dyke and the inner slope (the slope facing the water being the outer slope). This dataset is used to assess the liquefaction potential along the primary dykes in the governing area of WSHD. The potential for liquefaction is determined by the layer thickness of the contractive sand or the relative density of the material when it is less than 66%. If the relative density decreases or the thickness of the contractive sand layer increases the relative risk of liquefaction in the area increases.

Figure 1. Example liquefaction occurrence, 1968-10-04, Oud-Kempenshofstedepolder (Tholen), by Kotvis, (1986).

4 CURRENT NATIONAL GUIDELINES

The current Dutch Water Act (DWA, BWBR0025458) which came into effect on January 29th 2009, gives rules and design recommendations for the use and maintenance of Dutch water systems. The water governing authorities in the Netherlands are the primary executive organisations tasked with ensuring the water system and its defences comply with the DWA. Part of the DWA includes design rules for assessing direct and indirect failure mechanisms of dykes. With liquefaction recognised as one of the main indirect failure mechanisms, meaning that should an event happen, it will most likely not be the direct cause of a dyke failure but may contribute to one.

The recommended approach contains three assessments, each more detailed than the one before. The test are: a simple test, a detailed test, and a custom test. The methods of the simple and detailed test are prescribed in the technical guidelines whilst the custom test allows one to utilise the latest scientific insights to make the assessment.

The simple test is a geometric test with conservative assumptions. The detailed test considers soil properties, geometry, water levels and load types. The test itself determines whether there is enough dike forefront left after a liquefaction event to prevent failure (inundation). The DWA is revaluated regularly to incorporate the latest insights in water safety. The latest official code came into effect in 2017 (WBI 2017). While the next instalment is expected in 2023.

Currently there is a large difference in the complexity and as a result the level of detail required in parameter determination between the simple test and the detailed test. Incorporating information from the material behaviour chart into the simple test would allow the WSHD to identify areas more susceptible to liquefaction. This would facilitate them to focus their subsequent detailed assessments on areas with a high liquefaction hazard.

5 DETERMINING CONTRACTIVE ZONES

To identify whether a soil is contractive and subsequently susceptible to liquefaction, the following CPT based procedure developed by (Robertson 1990, Robertson 2016) has been followed. First measured q_c values are normalised into Q_t using the following relations see equations 1 to 3:

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \quad (1)$$

$$F_r = \frac{f_s}{q_t - \sigma_{v0}} * 100\% \quad (2)$$

$$q_t = q_c + u_2(1 - a) \quad (3)$$

Where Q_t is the normalized cone resistance, q_t is the cone resistance corrected for water effects, σ_{v0} is the current in-situ total vertical stress, σ'_{v0} is the current in-situ effective vertical stress, F_r is the normalized friction ratio, f_s is the measured sleeve resistance, q_c is the measured cone resistance, u_2 is the shoulder penetration pore pressure (behind cone tip) and a is the cone area ratio. When normalised CPT parameters have been obtained the soil behaviour indices I_c and I_B as well as the contractive dilative boundary (CD) can be obtained using the following relations, see Equations 4 to 8.

$$I_c = \left[(3.47 - logQ_t)^2 + (logF_r + 1.22)^2\right]^{0.5} \quad (4)$$

$$Q_{tn} = \left[\frac{q_t - \sigma_{v0}}{p_a}\right]\left(\frac{p_a}{\sigma'_{v0}}\right)^n \quad (5)$$

$$n = 0.381(I_c) + 0.05\left(\frac{\sigma'_{v0}}{p_a}\right) - 0.15 \quad (6)$$

$$I_B = 100(Q_{tn} + 10)(Q_{tn}F_r + 70) \quad (7)$$

$$CD = 70 = (Q_{tn} - 11)(1 + 0.06F_r)^{17} \quad (8)$$

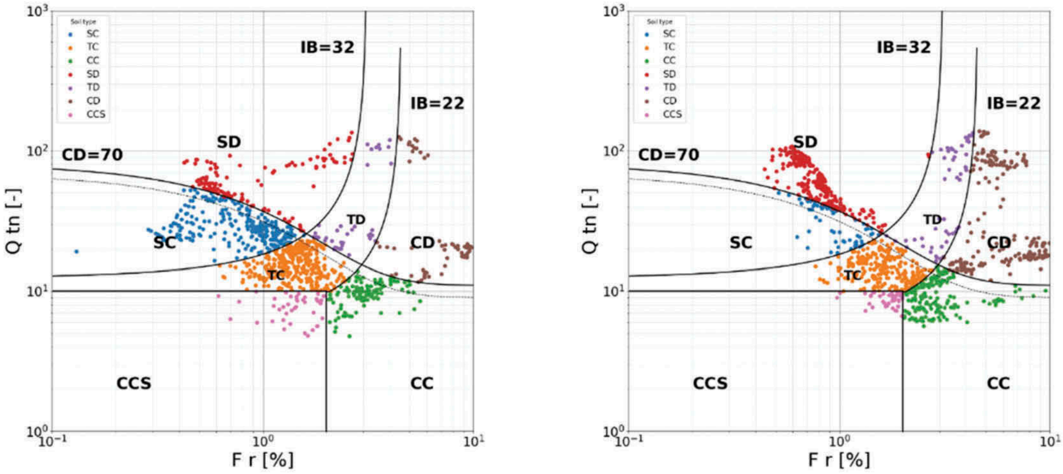
where p_a being the atmospheric reference pressure and n is the stress exponent defined by equation 6. After obtaining Q_{tn} and F_r and using the boundaries based on I_b and CD suggested by (Robertson 2016) the soil can be classified by the soil type behaviour. The relative density, D_r of young, uncemented silica sands (Kulhawy and Mayne 1990) can be obtained using:

$$D_r = \sqrt{\frac{Q_{tn}}{350}} \quad (9)$$

Figure 2 gives two examples of analysed CPTs using the soil behaviour chart as suggested by Robertson (2016). The following zones are named, CCS (clay-like, contractive, sensitive) CC (clay-like, contractive), CD (clay-like, dilative), TC (transitional, contractive), TD (transitional, dilative), SC (sand-like, contractive) and SD (sand-like, dilative). Figure 2a shows a CPT having a large number (606) of contractive points, and in Figure 2b fewer (296) contractive points are found.

6 IDENTIFICATION AND VISUALISATION OF LIQUEFACTION HAZARD

To identify the liquefaction potential the CPTs are automatically processed. For the calculation of



(a) (b)

Figure 2. Example soil behaviour chart after Robertson (2016) for two CPTs a) containing a large number (606) of contractive soil points and b) containing fewer (296) contractive points.

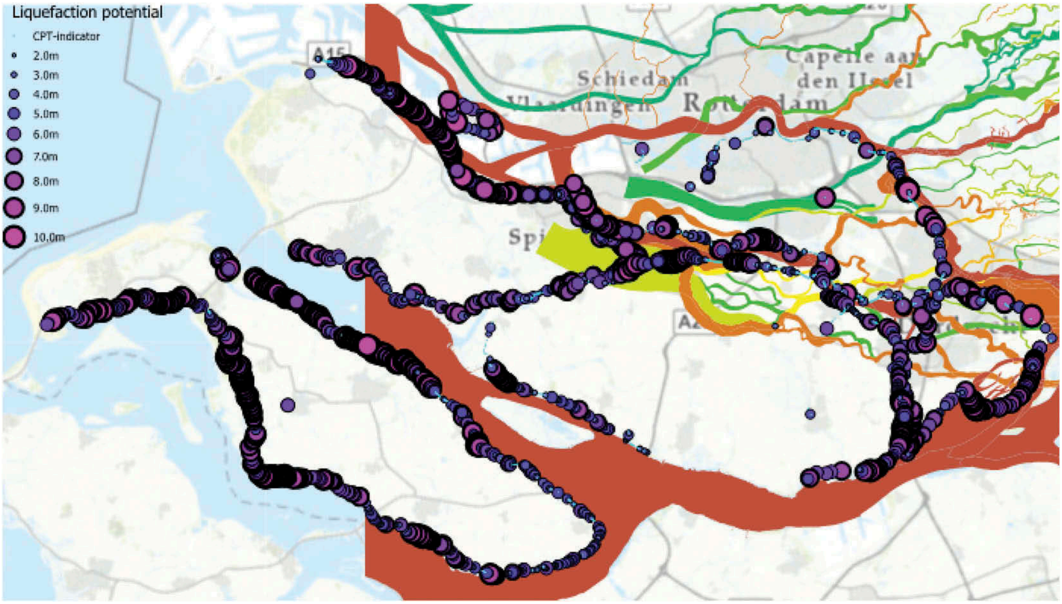


Figure 3. Governing area of WSHD overlaid with the old and current channel belts map, SC-SD-TC-TD 66% window is 200cm, CPT point size scaled to number of liquefaction susceptible points.

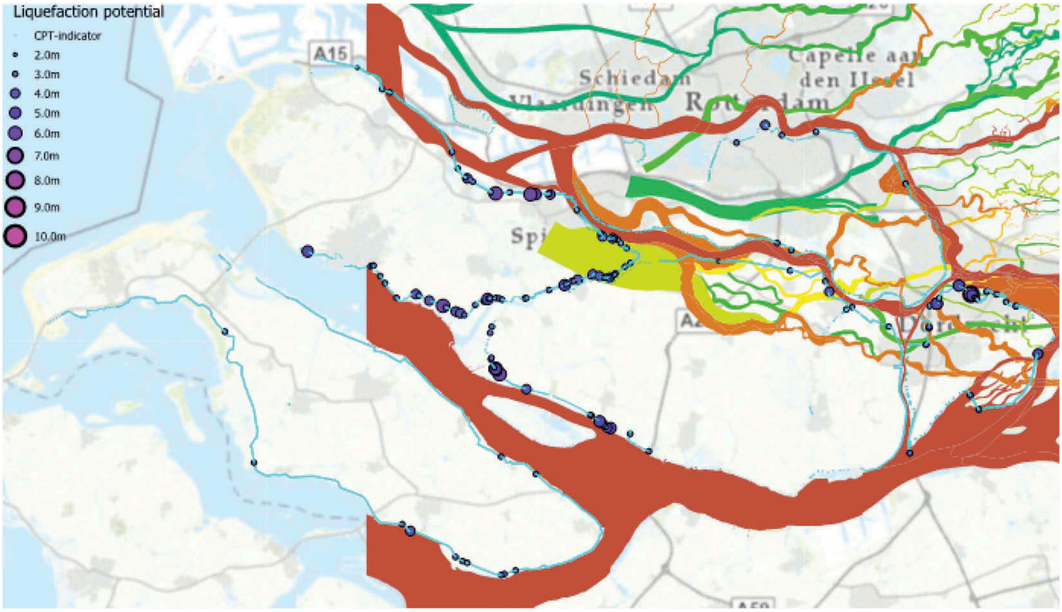


Figure 4. Governing area of WSHD overlaid with the old and current channel belts map, SC-TC 100% window is 200cm, CPT point size scaled to number of liquefaction susceptible points.

effective stress, the phreatic level is assumed to be fixed at the reference level of NAP +0.0 m with hydrostatic conditions assumed with depth. The liquefaction potential is analysed over a fixed depth of NAP +0.0 m to NAP -12.0 m. Each CPT is analysed using a moving window approach, once points in the window are identified as being susceptible to liquefaction, they are aggregated and the total number of susceptible points at a CPT location is used as an indicator of liquefaction hazard.

For all the CPTs analysed, two different criteria of liquefaction susceptibility have been used i) contractive sands and contractive transitional soils and ii) sands and transitional soils with a relative density below 66%. A moving window is used to tally the number of liquefaction susceptible points, the liquefaction susceptible points are counted if all points meet the requirement criteria. After processing, the highest liquefaction potential is associated to the highest number of concurrent liquefiable points.

Figure 3 shows the results of a batch analysis looking within all CPTs for zones that contain a relative density below 66% for transitional soils and contractive sands, it shows that most of the locations tested in the WSHD area contain significant volumes of loosely packed sand that may be susceptible to static liquefaction. Figure 4 presents the results for 2.0 m or larger continuous contractive sands and transitional soil layers. Figure 4 still highlights a number of liquefaction prone areas in the governing area of WSHD, however much fewer are identified than when the relative density approach is used.

7 DISCUSSION AND CONCLUSIONS

This paper presents two analyses performed using a large dataset of CPTs in the governing area of Waterschap Hollandse Delta (WSHD). Each CPT profile was analysed for the liquefaction susceptibility based on relative density and contractive behaviour. Based on the relative density analysis, many dykes were shown to be built on soil profiles containing significant depths of loose sand. This loose material has the potential to liquefy but does show consistent contractive behaviour over 2.0 m depths both according to the CPT analysis. The analysis based on the soil behaviour type highlights several locations where continuous depths of soil that would exhibit contractive behaviour are observed. As this has the potential to trigger liquefaction and cause large dyke failures to occur these areas will be more closly monitored by WSHD.

The analyses included some simplifications that can be examined in future studies. Rather than assuming hydrostatic pore pressures, an accurate assessment of in-situ pore water pressures should be conducted. The impact of dyke geometry and the resulting effective stress conditions should be included. Combining the liquefaction analysis with the geometry and bathymetry of the riverbed is an area of interest for the liquefaction susceptibility analysis. It is important to confirm the applicability of the relative density correlation and the trigger level of D_r below 66% to the Pleistocene sand layers considered. And finally, a major question remains, on what is the optimum moving window size for highlighting when contractive soil layers can cause large liquefaction induced failure.

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