Chapter 2
Field Measurements to Investigate Submerged Slope Failures

Alexander van Duinen, Adam Bezuijen, Geeralt van den Ham, and Victor Hopman

Abstract Many flood defences in The Netherlands have been disapproved for flow slides of the Holocene subsoil. Traditionally these flow slides are assumed to be induced by static liquefaction. Only in recent times it has been recognized that flow slides may also concern breach flows, which do not necessarily require loosely packed sand. For both static liquefaction and breach flow the inaccuracy of the currently applied methods to determine in situ density lead to high computed probabilities of failure, which is one of the main problems in the safety assessment of flow slides. In order to reduce this uncertainty, based on a literature study a number of methods were selected and applied on four test locations: two sites where flow slides occurred and two sites where no flow slides occurred, but for which high probabilities on flow slides were calculated based on current Dutch assessment rules for liquefaction and breach flow. For these sites CPT's and electrical resistivity cone tests available from earlier investigations, were extended with seismic CPT's and interpreted for relative density and state parameter. The results of this study lead to the conclusion that some of the historical flow slides in The Netherlands may have been the result of static liquefaction in loosely packed sand. For many other slopes, however, it is more reasonable to assume that the failures must have been breach flows in medium or densely packed layers.

Keywords Sand • Static liquefaction • Breach flow • Relative density • State parameter • Cone penetration test

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2.1 Introduction

Hundreds of flow failures of submerged slopes have been observed in the southwestern estuary of The Netherlands (Zeeland) since 1800. It is generally assumed that many of these flow failures are initiated by static liquefaction in loosely packed sand. However, in recent times it has been recognized that many of these flow slides may also concern breach flows, which do not necessarily require loosely packed sand.

The soil layers that might experience static liquefaction or breach flow are part of tidal and coastal deposits. These deposits contain alternating fine sand and clay laminae. The geological past of the southwestern estuary and the coast of The Netherlands is characterised by rapidly shifting coastlines and alternating sedimentation and erosion along the tidal channels and the coast. Generally the upper 30 m of the subsoil consists of Holocene deposits. Most of these consist of (medium) fine sand, which, in general, is loosely packed due to high deposition rates. The variation in tidal currents often resulted in the deposition of thin clay layers in between the thicker sand layers.

In a loosely packed sand layer static liquefaction can occur, given a sufficiently high and steep under water slope and the presence of a trigger, such as a local slip failure or rapid drop of water level. Static liquefaction involves the sudden undrained collapse of the soil structure leading to an increase of pore water pressure, resulting in a dramatic reduction of shear strength and consequently instability of the slope. In densely packed sand, a breach flow can occur. A breach flow entails the upslope retrogression of a breach, induced by erosion or scour. According to de Groot and Mastbergen (2006) and van den Ham et al. (2013) it is reasonable to believe that many flow slides in the Holocene tidal and coastal deposits, which are characterised by alternations of densely and loosely packed sand layers, concerned combinations of static liquefaction and breach flow.

According to the current Dutch assessment procedures (Rijkswaterstaat 2007; TAW 2001) a large number of levees in the Netherlands are not sufficiently safe with respect to flow sliding. Besides uncertainty in the models for liquefaction and breach flow, a large part of the relatively high calculated probabilities of failure can be ascribed to the large uncertainty of the in situ void ratio of the sand, which is relevant for both static liquefaction and breach flow and is an important input parameter of the calculation models.

In this paper (i) various published interpretation methods to determine the in situ void ratio of sand and silt are given, (ii) application of a number of these methods on four test sites is presented and (iii) conclusions are drawn with respect to the accuracy and practical applicability of the methods are given.

The deposits at four sites are investigated. At Oude Tonge and Hoofdplaat (both in Zeeland) a failure occurred (1972 and 1973 respectively). Stoutjesdijk and de Groot (1994) found that these failures could have been caused by static liquefaction. Tabak (2011) analysed the failure at Oude Tonge and found that this failure could also be explained as a breach flow failure. At the sites at the river Spui (near

Oud-Beijerland) and Petten (along the Noordzee) no failures occurred, but for these sites calculation models yielded unacceptably high probabilities of failure. The soil layers at these four sites belong to the same geological deposits as described above. The site investigations were carried out with CPT trucks and CPT track rigs on land, in the zone between the dikes and the shoreline.

2.2 Interpretation Methods of Field Measurements

2.2.1 Relative Density

In Dutch practice relative density is today the most widely used expression to estimate the susceptibility for static liquefaction. An estimation of the in situ relative density can be made using a correlation with the cone tip resistance (q_c) of a cone penetration test (CPT) or directly with the electric resistivity of a resistivity CPT (RCPT). In the literature, several CPT correlations are available. In the Dutch engineering practise the correlation of Baldi et al. (1982) is often used, because this correlation estimates the relative density in the middle of other well-known relative density correlations.

According to the (roughly chosen) criteria generally applied in the Dutch engineering practice a relative density below 33 % indicates very liquefiable sand, a value between 33 and 67 % indicates potentially liquefiable sand and above 67 % the sand is assumed to be not liquefiable (i.e. dilative).

In none of the relative density correlations is the effect of fines taken into account and in most of them the soils' compressibility neither, whereas it is known that fines are an important factor of influence to the susceptibility of a sand layer to liquefaction (Lade et al. 2009) and variations in soils' compressibility may lead to 15–20 % deviation of the average relative density, as can be concluded from Schnaid (2009). In some of the correlations the importance of soil compressibility has been recognized (i.e. Kulhawy and Mayne 1990; Jamiolkowski et al. 2001). However, today there is no approach to quantify the effect of the soil compressibility in the CPT based relative density estimation.

Most relative density correlations assume drained behaviour during the CPT.

2.2.2 State Parameter

The state parameter, ψ, introduced by Been and Jefferies (1985), is defined as a measure of the deviation between the void ratio at the in situ state and the void ratio at the critical state. A negative ψ indicates dense, dilative soils, whereas a positive ψ indicates loose contractive soils. Been et al. (1987) developed an approach to derive ψ from a CPT. After the Been et al. (1987) approach other approaches were formulated, varying from simple screening methods based on CPT only to advanced methods requiring seismic CPT (SCPT) and laboratory tests. The most important are (i) the screening method of Plewes et al. (1992), including partially drained conditions with the normalized excess pore pressure B_q and estimating the soil compressibility λ from the normalized friction ratio F_r, (ii) the screening method of Been and Jefferies (1992), including partially drained conditions with the normalized excess pore pressure B_q and estimating the soil compressibility λ from the soil type index I_c, (iii) the Shuttle and Jefferies (1998) universal framework, which accounts for in situ soil stiffness G_0, plastic hardening modulus H and stress level bias, (iv) the Schnaid and Yu (2007) theoretical approach, which relates ψ to the ratio of the cone tip resistance q_c and the small strain stiffness G_0, (v) the method of Robertson (2010), which is a simplified and approximate relationship between ψ and the normalised equivalent clean sand cone tip resistance $Q_{tn,cs}$ and (vi) the method of Ghafghazi (2011), who extended the Shuttle & Jefferies framework and performed spherical cavity expansion analysis with a finite element model.

An important shortcoming of some of the listed state parameter interpretation methods is that they are only valid for completely drained cone penetration, with pore pressure parameter $B_q \approx 0$, whereas in clayey sands (substantial) excess pore water pressures may be generated during cone penetration. The Plewes et al. (1992) screening method and the Been and Jefferies (1992) screening level assessment are initial steps to estimate the state parameter for partially drained soils. However these methods are first approximations and might be argued as rather speculative (Jefferies and Shuttle 2011). Shuttle and Cunning (2007) and LeBlanc and Randolph (2008) developed a more advanced approach for partially drained soils. DeJong et al. (2012) suggest modifying the penetration rate of the CPT to obtain fully drained or fully undrained soil behaviour. But these methods need further development and validation (Jefferies and Shuttle 2011; DeJong et al. 2012).

2.3 Application on Test Locations

Figures 2.1, 2.2, 2.3, and 2.4 present typical values of the normalized cone tip resistance Q_t, $(= (q_t - \sigma_{v0})/\sigma'_{v0})$, normalized shear wave velocity V_{s1}, normalized pore pressure parameter B_q, Been and Jefferies (1992) soil behaviour index I_c, which include the pore pressure parameter B_q, state parameter ψ and relative density R_e of the four investigated sites respectively. Both the results of the state parameter interpretations of Plewes et al. (1992) and Shuttle and Jefferies (1998) are shown. The normalized shear wave velocity V_{s1} from SCPT, soil compressibility λ and friction angle φ' from triaxial tests and estimations of the hardening modulus H are used in the Shuttle and Jefferies (1998) method. Relative density is in each case calculated from the cone tip resistance with the Baldi et al. (1982) correlation and derived from the resistivity cone (R_e A and R_e B) according to de Graaf and Zuidberg (1985). The state parameter and the relative density are only presented

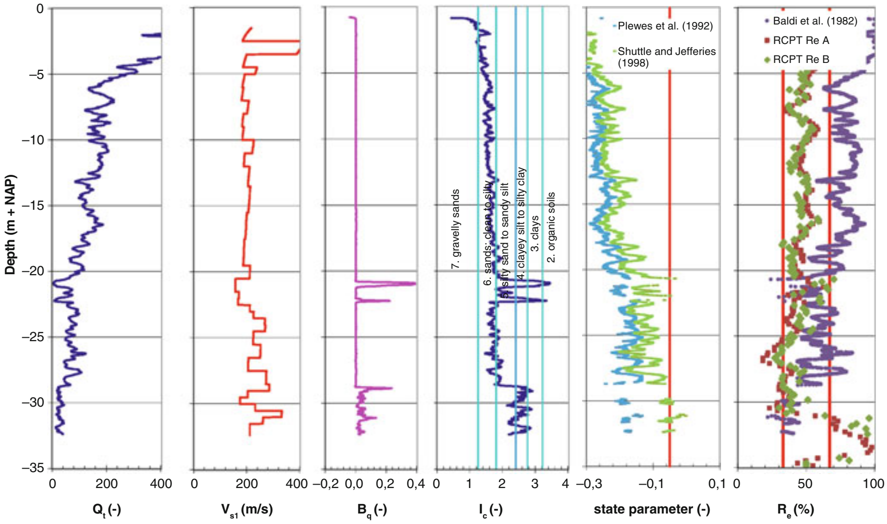

Fig. 2.1 Results and interpretations of Oude Tonge

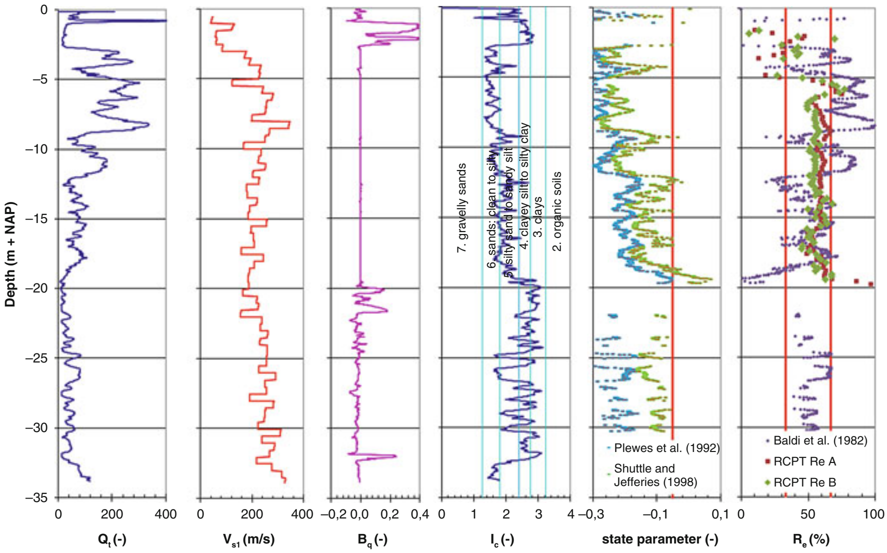

Fig. 2.2 Results and interpretations of Hoofdplaat

if $I_c < 2.4$. The boundary between contractive and dilative response suggested by Shuttle and Cunning (2007) at $\psi = -0.05$ is shown on each figure as well as the relative density boundaries of 33 and 67 %.

At Oude Tonge (Fig. 2.1) the soil behaviour index I_c indicates mainly clean sand to silty sand to a depth of 28 m below the reference level NAP. Below NAP –28 m the

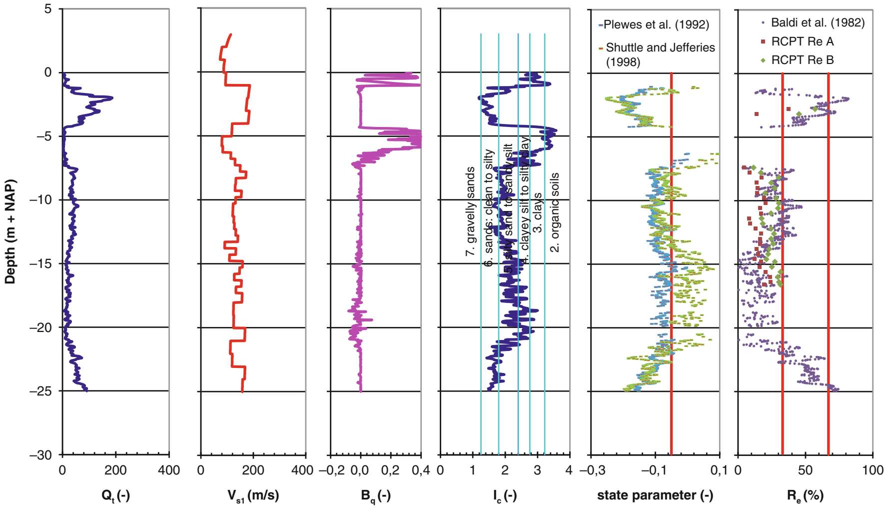

Fig. 2.3 Results and interpretations of Spui

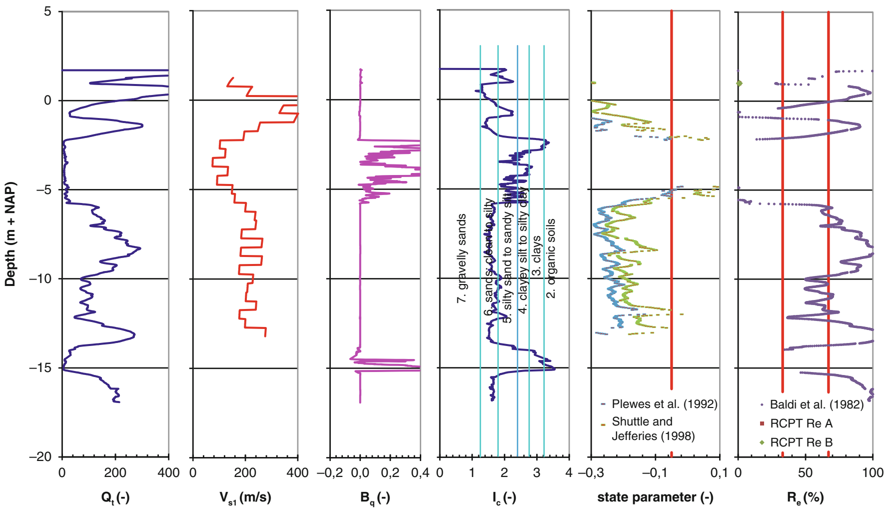

Fig. 2.4 Results and interpretations of Petten

soil behaviour index indicates clayey and silty material. The sand deposit behaves dilative according to the state parameter interpretations ($\psi < -0.05$). According to the relative density as calculated with the Baldi et al. correlation the sand layer behaves dilative above NAP –18 m only. The relative density derived from the resistivity cone indicates generally potentially liquefiable sand (33 % < R_e < 67 %) and very liquefiable sand around NAP –27 m (R_e < 33 %).

At Hoofdplaat (Fig. 2.2), the soil behaviour index I_c shows mainly clean sand to silty sand above NAP –19 m. Below NAP –19 m the deposits are alternations of sandy, silty and clayey layers. Again the state parameter interpretations indicate dilative behaviour of the above silty sand layer. The relative density from the Baldi et al. correlation and the relative density from the resistivity cone are in reasonable agreement at this site. Both results indicate potentially liquefiable sand in the deposit above NAP –19 m.

At Spui (Fig. 2.3), the deposits between NAP –8 m and NAP –22 m are indicated by the soil behaviour index as silty sand and sandy silt with various thin layers of clayey silt and silty clay. Between NAP –8 m and NAP –13 m the silty sand layer is very liquefiable according to the relative density methods. In the most clayey part of the deposit below NAP –13 m both the Shuttle & Jefferies state parameter interpretation and the relative density calculated from the Baldi et al. correlation show very liquefiable sand. However the Plewes et al. interpretation, which includes pore pressure effects, gives a state parameter which indicates dilative sand behaviour. This is an interesting result, because the soil behaves partially drained ($B_q \neq 0$).

At Petten (Fig. 2.4), the soil layer between NAP –4 m and NAP –6 m is of particular interest. This layer is characterised as silty sand to silty clay (sand with up to 9 % silt and 7 % clay). Both the state parameter interpretation of Shuttle & Jefferies and the relative density methods indicate this layer as potentially liquefiable to very liquefiable. Again the Plewes et al. method classifies this layer as mainly dilative.

2.4 Discussion

Some important reasons argue in favour of application of the state parameter as the most suitable method for defining the in situ state of sand. Compared to relative density the state parameter is a more objective measure and has a better theoretical basis. The Shuttle and Jefferies (1998) universal framework uses physical parameters of the soil behavior, which can be derived from field and laboratory tests. Thus an accurate state parameter determination can be made for each sand deposit and each site, which account for fines content, soil compressibility and soil stiffness.

At the four investigated locations the state parameter approach indicates less liquefiable sand (i.e. more dilative sand) compared to the traditional Dutch assessment criteria based on relative density. The $\psi = -0.05$ state parameter boundary between dilative and contractive response seems to correspond with the $R_e = 33$ % relative density boundary. Sand with a relative density between 33 and 67 % seems to be not liquefiable according to the state parameter methods.

A remarkable result is that at the locations where flow slides occurred, i.e. Oude Tonge and Hoofdplaat, the sand deposits appear to be denser, based on CPT interpretation, than those at Spui and Petten, where no flow slides occurred. From the traditional Dutch point of view in which flow failures are assumed to be the result of static liquefaction in loose sand deposits this seems to be a paradox.

The findings could be explained by a number of reasons: (i) other conditions required for flow slides at each site were different, such as height and steepness of the slope or the absence of changing geometry by sedimentation and erosion, (ii) the two slope failures concerned breach flow slides in densely packed dilative sand (triggered by erosion of the slope) as could be underpinned by calculations with a breach flow model by Tabak (2011), (iii) the two slope failures are initiated by static liquefaction in a thin layer of loose sand, triggering a breach flow as soon as liquefaction induced instability reached the dense sand, (iv) at Spui and Petten the void ratio of the sand layers is underestimated due to partially drained conditions during cone penetration that were not taken into account. The sand at Oude Tonge and Hoofdplaat behaves more or less drained compared to the other two locations.

2.5 Conclusions and Recommendations

This study underpins that not only static liquefaction of the loosely packed Holocene deposits but also breach flow in densely packed deposits has to be evaluated in the safety assessments of flood defences. This study makes clear that, as already suggested by Tabak (2011), flow failure is possible also in denser sand in the form of a breach flow. This makes it worthwhile to further investigate the breaching failure mechanism (for which conditions it occurs, what trigger is necessary etc.). For a clear understanding of the slope failures at Oude Tonge and Hoofdplaat and to understand why no failures have yet occurred at Spui and Petten further study is required. Relevant aspects of CPT interpretation might be the drainage conditions during cone penetration and the effect of aging on cone tip and shear wave velocity measurements (Wride et al. 2000).

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