ASSESSING UNDRAINED SHEAR STRENGTH IN DANISH MARINE GYTTJA: INSIGHTS FROM FIELD VANE TESTS AND PLATE LOAD TESTS

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KEYWORDS

Soft soil deposits, field vane tests, undrained shear strength, plate load tests, marine gyttja

ABSTRACT

In Denmark, the presence of soft soil deposits in construction projects has gained a lot of attention due to more focus on sustainability, a decreasing access to natural granular fill materials and a laboured process of permits from the authorities to deposit unusable soft soils onshore and offshore.

Field vane tests (FVT) have a long tradition of being the most common field investigation method for assessing the undrained shear strength of cohesive fine-grained soils in Denmark. For soft soils, the conversion from field vane strength (c_{fv}) to undrained shear strength (c_u) is currently a rather uncertain task and conservative estimates of the c_{fv}/c_u ratio is often set to cover this uncertainty in geotechnical designs resulting in overconsumption of materials.

To gain basis for a better understanding of the c_{fv}/c_u ratio and hence narrow the uncertainty, plate load tests (PLT) have been performed on Danish marine gyttja of various plasticity, for direct measurement of c_u. At the same locations, FVTs have been carried out and intact samples (Shelby tubes) of gyttja have been recovered from geotechnical boreholes for determination of c_u by undrained triaxial tests.

The results show a decrease in the c_{fv}/c_u ratio with increasing plasticity index analogous to results found by Bjerrum for (primarily) mineral deposits, however the results furthermore indicate that the empirical correlations suggested in literature tend to result in too conservative estimates of c_u.

1. INTRODUCTION

Background

The current urban growth and the need for public transport and services are leading to increased demand for new buildings and infrastructures. However, the lack of urban space and the desire to optimize infrastructure locations result in the need to build on soft soil sites with challenging conditions, frequently found in wetland and coastal areas. Recently, disposal of soft organic deposits (gyttja, peat, high plasticity organic clay) has gained a lot of political and public attention due to media coverage of major construction and landfill projects. Soft soils are, due to their problematic material properties with low strength and stiffness, often disposed and replaced by dwindling natural granular fill resources or expensive (economical and CO_2-wise) lightweight expanded clay. The increased public and media attention labours the process of permits from the

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authorities to dispose or dump soft soil putting pressure on the clients and hence the consultants to utilise the soft soil deposits within the projects. The present paper focuses on estimations of undrained shear strength of marine postglacial gyttja.

Danish marine gyttja

The Danish marine postglacial gyttja is typically found in the coastal and wetland areas of Denmark as indicated on Figure 1 (left). Marine gyttja is characterized by its organic origin often mixed with mineral content as a result of activity of bioturbators on the sea floor. The plasticity index, *PI*, of Danish gyttja usually ranges from less than 5% to 200%, but values of 250% or more are occasionally observed.

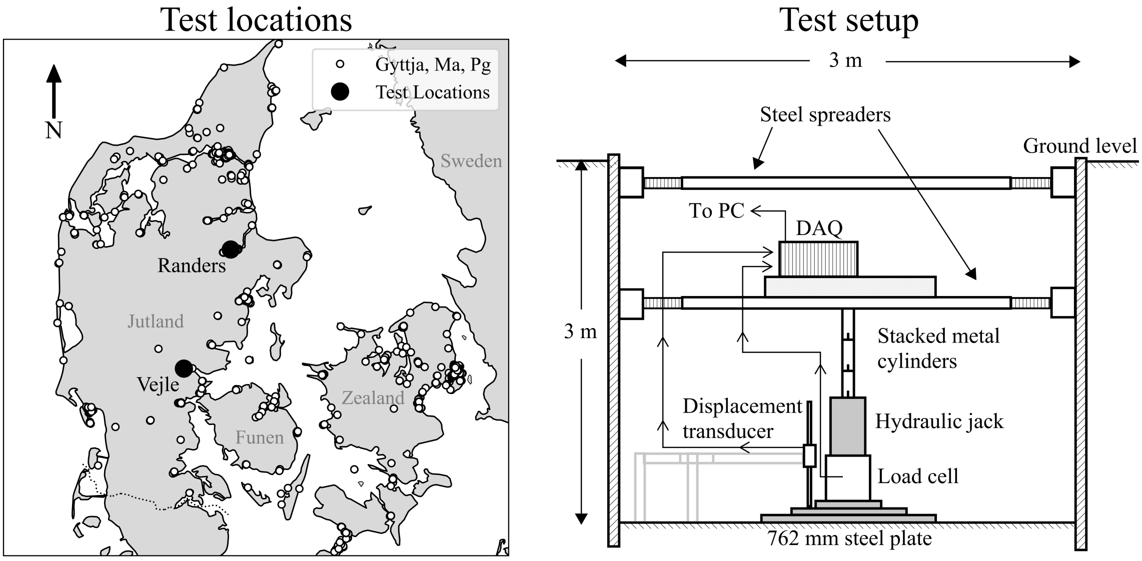

Figure 1: Map of Denmark showing boreholes (>2100) containing marine postglacial gyttja and location of test sites at Randers and Vejle (left) and sketch of plate load test setup (right).

Field vane tests

Since its invention in 1947 [1] and introduction to Danish engineering practice in the early 1950's the field vane test has been and still is considered as one of the most cost-effective, practical and convenient methods for assessing the undrained shear strength of cohesive fine-grained soil in-situ [2]. It often serves as a reference for Danish literature, experience and in situ soil strength. In Denmark, the concept and equipment itself is similar to standardised procedures in other Nordic countries but the Danish procedure has been developed to cover a wider range of shear strengths ($10 < c_{fv} < 700$ kPa) and the test rate is set to be significantly faster [2] – standardised by Danish Geotechnical Society to aim for one revolution per minute [3].

Field vane correction factor

The ultimate undrained shear strength of soils is their ability to resist a load during constant volume and a specific set of conditions (effective stresses, temperature, pore water chemistry, shear rate, constraints, mode of shearing etc.). Hence, the undrained shear strength of a specific soil (sample) is not unique but dependent on the conditions during shearing. Therefore, various methods for assessing the undrained shear strength will provide different results.

It is commonly accepted that the measured field vane strength, c_{fv}, is generally not equal to the average undrained shear strength typically used for failure analyses. To take into account the effects of progressive failure, anisotropy, shear rate and plasticity L. Bjerrum [4] suggested adjusting the field vane strength, c_{fv}, by a factor μ, dependent on the plasticity index, *PI*, to yield a bette r estimation of the undrained shear strength, $c_u = \mu(PI) \cdot c_{fv}$. A similar, but apparently bilinear, concept was officially adopted in Danish practice in 1977 [5]. The concept was modified in 1984 [6] to mimic that of L. Bjerrum [4] by

$$\frac{c_u}{c_{fv}} = \mu = \frac{1.2}{1 + 0.01 \cdot PI} \leq 1.0 \quad (1)$$

to be used for organic clay. The basis for the curve suggested by L. Bjerrum eq. (1) was a comprehensive compilation of failures and landslides in low plastic clays from Norway and clays with varying plasticity from mainly Europe and North America. No high plasticity ($PI > 115\%$) or organic soil from Scandinavia was evaluated. Organic soils were considered but mainly organic Bangkok clay.

Even though some literature suggests that back calculations of failures in (Danish) gyttja agree with the equation (1) i.e. [7] there seems to be no documented research confirming this issue. Some published literatures have tried to evaluate the validity of eq. (1) by correlating results from undrained triaxial tests on gyttja and organic clay with representative field vane tests showing a significant scatter [2]. The current authors contend that the observed correlation frequently exhibits unreliability, primarily attributable to the significant influence of errors stemming from the test procedure and sample disturbance. This is particularly relevant in the context of soft soils, and even more so with gyttja, given their inherently low strength and stiffness.

An alternative approach to that of L. Bjerrum, recommended by the Swedish Geotechnical Institute (SGI), relies on the liquid limit, w_L, rather than the plasticity index [1]:

$$\mu = \left(\frac{0.43}{w_L}\right)^{0.45} \cdot \left(\frac{OCR}{1.3}\right)^{-0.15} \quad (2)$$

where $1.2 \geq \mu \geq 0.5$. The idea of reducing field vane strength and fall cone test results by a factor that is influenced by the liquid limit to estimate the undrained shear strength was already initiated in the 1950's yielding different correction factors, culminating in the first SGI correction factor in 1969. The basis for equation (2) was originally developed for organic and high plasticity clays [8] and eq. (2) is currently recommended for organic clay and soft soils [9].

2. TEST SITES

In an attempt to yield a reliable estimate of the actual mean (across the failure line) undrained shear strength governing failure and to assess the validity of eq. (1) and eq. (2) two series of plate load tests have been performed on marine gyttja at two different locations in Denmark. To evaluate the validity of the field vane tests, oedometer tests and one series of triaxial and direct simple shear tests on the marine gyttja have been performed.

Test locations

Two different test locations were chosen based on the following criteria: 1) marine postglacial gyttja near terrain 2) expected high plasticity index 3) constant c_u (or c_{fv}) with depth 4) accessibility. Trawling various borehole databases against the mentioned criteria was automated to locate the apparently most suitable locations. A test site in Randers, near the fjord, and a test location at Vejle Fjord was chosen for the plate load test series. Figure 1 shows the test locations at Randers and Vejle.

Geology and classification

Figure 2 shows the stratigraphic profiles from the test sites at Randers and Vejle based on the results from two geotechnical boreholes at each site executed prior to the plate load tests. Both sites are dominated by marine post glacial gyttja immediately or close to the ground level. In Randers the gyttja is covered by a thin layer of top soil and vegetation and in Vejle the gyttja is covered by approximately two metres of fill from reclamation and extension of the city of Vejle into the fjord between 1945 and 1976. The gyttja from Randers and Vejle is generally described as clayey, slightly silty (Randers) and high plasticity (Vejle), suggesting the gyttja found in Vejle to possess a greater plasticity index compared to that of Randers.

At both locations the gyttja is underlain by postglacial marine sand deposits. At Randers the field vane strengths and the water contents are rather constant ($c_{fv} \approx 20$ kPa, $w \approx 100\%$) with depths greater than approximately 2.5 metres. At the Vejle test site, the water contents are more scattered at depths greater than 3 metres, with water content ranging approximately from 100 to 200% ($w \approx$ 100 to 200%). In contrast, the field vane strengths are almost constant, with values around 20 kPa ($c_{fv} \approx 20$ kPa). Although not directly related, it is expected for the field vane strength (or shear strength) to display a trend with depth opposite that of the water content (assuming constant *PI*). This can possibly be explained by the test methods (FVT and water content measurement) not being equally sensitive in the low strength gyttja and c_u and w not being linearly related.

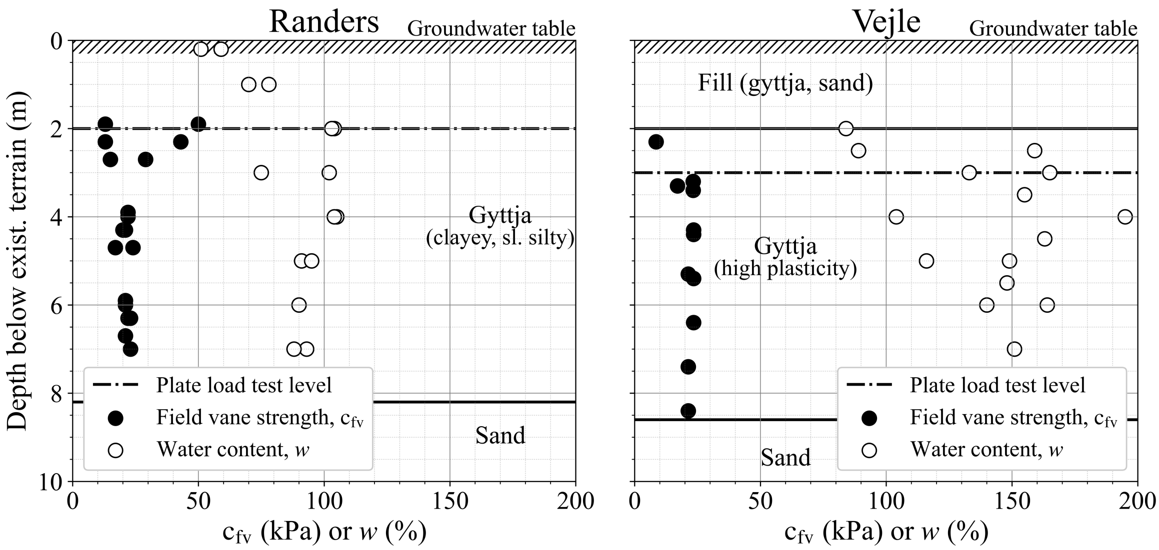

Figure 2: Stratigraphic profiles for test site locations Randers (left) and Vejle (right) including the approximate level for execution of the plate load tests. Based on two geotechnical boreholes at each site.

The plasticity index, *PI*, and the liquid limit, w_L, range from 47 - 57% (mean = 51%) and 96 - 98% (mean = 97%), respectively, in Randers and 74 – 83% (mean = 79%) and 169 – 179% (mean = 174%), respectively, in Vejle. The Atterberg limit tests support the geological descriptions suggesting the gyttja at the Vejle test site to possess a greater plasticity index.

3. TEST METHOD

Plate load tests

Figure 1 (right) shows the plate load test setup. The plate load tests were setup in 3 m wide trench boxes to reduce excavation volumes and costs. In addition to retaining the soil the weight of the trench boxes was used as dead load for the plate load tests. The test area within the trench boxes was prepared in accordance with BS 1377 [10] and allowed levelling of the test level at least three times the plate radius at each test the complying with recommendations from the Danish Geotechnical Society [11].

The transmission of force from the fixed support (trench box) to the loading plates was done by stacking solid metal cylinders of varying sizes each with a pin in one end a socket in the other end. The test plates were 762 mm diameter steel plates in accordance with DIN 18134 [12].

The load increments were applied at a constant penetration rate, increasing the applied stress by 5 kPa within 1 minute, followed by maintaining this stress level for an additional minute. In accordance with BS 1377 [10] it was striven to reach a displacement of at least 15% of the plate diame ter, equivalent to 114 mm displacement or until a well-defined failure plateau is observed as suggested in ASTM D1194 [13]. At total of 10 and 5 plate load tests were performed at Randers and Vejle, respectively.

Field vane tests

In Randers the FVTs were conducted at depths ranging from 0.2 to 0.4 m beneath the centre of the plate load test and in Vejle they were performed in the immediate vicinity of the plate load tests. The FVTs were performed immediately before the commencement of the PLTs. The authors have assessed that the FVTs are unlikely to exert a significant or measurable influence on the outcomes of the plate load tests. The FVTs were performed and assessed according to Danish standard [3], using vane type V9.5 at Randers and V7.5 at Vejle. A total of 20 and 10 field vane tests were performed by hand at Randers and Vejle, respectively, after excavation. The field vane test results were calibrated according to Danish practice [3].

Laboratory tests

Triaxial tests (compression and extension), direct simple shear tests (DSS) and oedometer tests (IL) have been performed on gyttja samples from the Randers test site. Only oedometer tests (CRS) have been performed on gyttja from the Vejle test site. Based on results from oedometer tests, the overconsolidation ratios (*OCR*) range between 1 – 2 in Randers and 1 – 1.2 in Vejle.

4. ANALYSIS

Plate load tests

Figure 3 shows the load-displacement curves from the plate load tests performed at Randers (left) and Vejle (right). The displacements are normalised by the plate diameter (762 mm) to yield the displacement ratio, r_δ = displacement/plate diameter.

In Vejle the tests were limited by loss of effect of the metal cylinders transmitting the forces between the fixed support and the load cell. This happened due to small gradual rotation of the load plates causing the cylinders to shoot out resulting in loss of load transmission. The same limiting effect was also learned at the Randers test site but several tests were successfully strained beyond the maximum applied stress yielding the post-peak behaviour.

The load-displacement response is observed to behave rather differently in Randers and in Vejle. The load-displacement curves from the tests at the Randers site generally mimic that of a foundation on stiff soil (clear plateau of failure) and the Vejle tests as a foundation on soft soil (increasing stress towards an asymptote, or linear increase, with deformation and no clear failure or elbow).

To yield a consistent evaluation of the maximum applied stress, q_{max}, considering the different stress-deformation behaviour of the plate load tests from the two test sites, the inference of q_{max} is evaluated as the maximum applied stress within a displacement ratio, r_δ = 10%, equivalent to 76 mm deformation. This approach is recommended by BS 1377 if no clear failure plateau is observed, though suggesting a displacement ratio, r_δ = 15% [10]. As the majority of the PLTs in Vejle were limited before reaching $r_\delta = 10\%$, the load-displacements curves are extrapolated to $r_\delta = 10\%$.

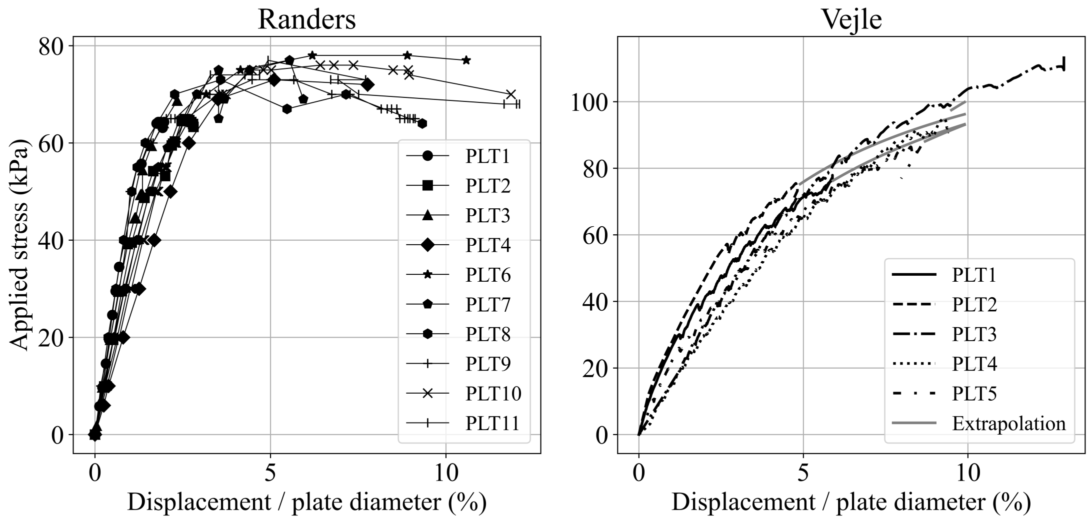

Figure 3: Results of plate load tests on marine gyttja from the plate load test site locations in Randers (left) and Vejle (right).

Back calculation of undrained shear strength

To estimate the mean undrained shear strength from the plate load test results, the following equation is used:

$$q_{\max} = c_{\mathrm{u.PLT}} \cdot N_c^0 \cdot s_c^0 \tag{3}$$

where $c_{\mathrm{u.PLT}}$ is the mean mobilised undrained shear strength, N_c^0 is the undrained bearing capacity factor and s_c^0 is the shape factor. In the case of stiff or dense soil (a stress-deformation response with a clear plateau at failure), a bearing capacity factor of $N_c^0 = 2 + \pi \approx 5.14$ is well established. A shape factor of $s_c^0 = 1.2$ [14] corresponding to a completely rough interface between a circular plate and the soil surface is used, resulting in

$$q_{\max} = c_{\mathrm{u.PLT}} \cdot 6.17 \tag{4}$$

assuming a fully developed circular failure surface.

Field vane correction factor

The field vane correction factor is calculated as:

$$\mu = \frac{c_{\mathrm{u.PLT}}}{c_{\mathrm{fv}}} \tag{5}$$

where $c_{\mathrm{u.PLT}}$ and c_{fv} are the undrained shear strength inferred from back calculation of results from plate load tests and the field vane strength, respectively.

As the plate load tests and the field vane tests are performed under the approximately same conditions (temperature, effective stresses etc.) at the individual test sites, μ is derived based on average values of $c_{\mathrm{u.PLT}}$ and c_{fv} making the result of μ less sensitive to outliers. This assumption seems reasonable for the reasons that 1) the field vane activates only a small volume of soil and only two FVTs were performed at each PLT, making the local mean highly sensitive to outliers. Furthermore, the PLTs at the individual test sites behave rather uniformly, indicating little variation in the soil behaviour. 2) As statistical methods to estimate averages are used more and more, correction factors should be based on averages as well [8]. 3) The correction factor proposed by L. Bjerrum was established on averages of the shear strength values measured by shear vane tests [8]. Table 1 summarises the inferences of μ from the two test locations using the above-mentioned approach.

Table 1: Inference of μ from plate load tests and field vane tests performed in gyttja at the test site locations in Randers and Vejle.

Location	c_{fv} (kPa) [a]				$c_{u.PLT}$ (kPa) [b]				μ (-) [c]
	No. of tests	Mean	Min.	Max.	No. of tests	Mean	Min.	Max.	
Randers	20	14.2	10.2	17.1	10	12.2	11.8	12.6	0.86
Vejle	10	20.0	18.0	24.6	5	15.8	15.1	16.8	0.79

[a] c_{fv} with vane types V9.5 at Randers and V7.5 at Vejle

[b] $c_{u.PLT} = q_{max}/6.17$

[c] $\mu = c_{u.PLT.mean}/c_{fv.mean}$

To estimate the relative impact of variations in c_{fv} and $c_{u.PLT}$ on μ, the change in μ with $c_{u.PLT}$ is computed by $\Delta\mu_{cuPLT} = (c_{uPLTmax} - c_{uPLTmin})/c_{fvmean}$ and vice versa for the relative impact of variations in c_{fv}. In Randers $\Delta\mu_{cuPLT} = 0.06$ and $\Delta\mu_{cfv} = 0.48$, indicating the variations in the PLT results to be negligible. A similar, though less pronounced, trend is supported by the results from Vejle where $\Delta\mu_{cuPLT} = 0.09$ and $\Delta\mu_{cfv} = 0.23$. These findings suggest $\Delta\mu$ to primarily reflect the variation in c_{fv} rather than variation in undrained shear strength (bearing capacity).

Figure 4 illustrates the inferred μ against the plasticity index, PI and the liquid limit, w_L, including existing data and the correlations suggested in literature given by eq. (1) and eq. (2). The results are based on average values of c_{uPLT} and c_{fv}. Table 2 summarises the soil types and sources of the existing data plotted on figure 4.

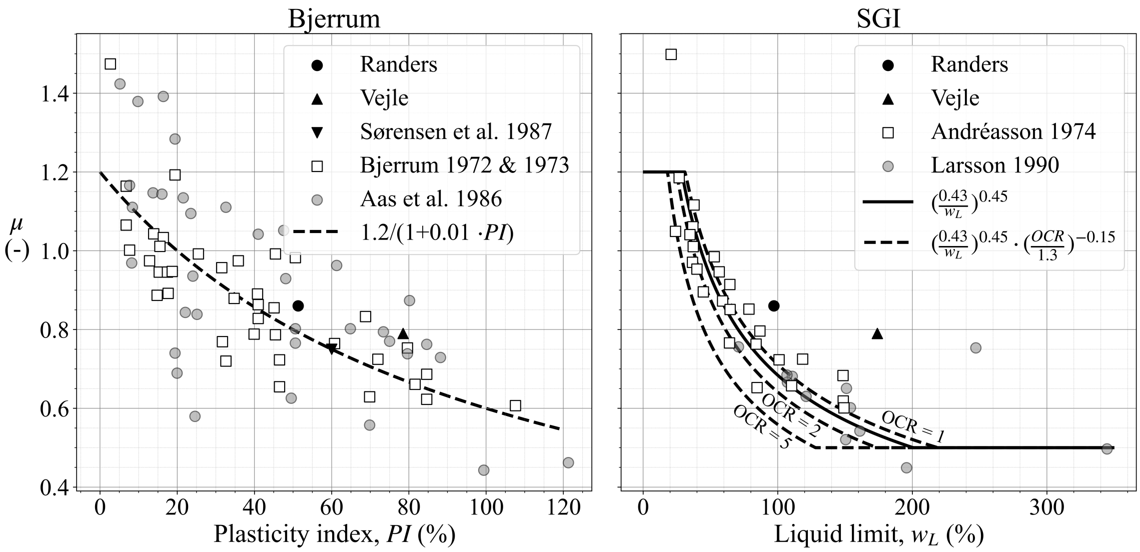

Figure 4: Inferred μ against plasticity index, PI including existing data (left) and liquid limit, w_L including existing data (right) from plate load test results and field vane tests at test sites in Randers and Vejle.

Table 2: Sources and soil types for existing data plotted on figure 4.

Identification (figure 4)	Soil types	Method*	Source
Bjerrum 1972 & 1973	Low plastic European and North American clays, organic Bangkok clay	BC, PLT	[4] & [15]
Aas. et al. 1986	Clay	Unknown	[16]
Sørensen et al. 1987	Gyttja	BC	[17]
Andréasson 1974	Recalculation of Bjerrum 1972 & 1973	BC	[8]
Larsson 1990	Gyttja and organic clay	L, BC	[9]

* BC = back-calculation (full scale failures), PLT = plate load tests, L = laboratory tests

The Bjerrum curve in figure 4 (left) is observed to be a conservative estimate in relation to the test results from Randers and Vejle. The test results from both Randers and Vejle are observed to lie above the Bjerrum curve within the scatter of the original data for the curve fit and supplementary data (primarily mineral clay). The original data collected by L. Bjerrum and the supplementary data collected by Aas. et al. show considerable scatter. Considering the present mean plasticity indices PI_{Randers} = 51% and PI_{Vejle} = 79%, the Bjerrum curve underestimates μ by 0.06 and 0.12, respectively. As the basis for the Bjerrum curve primarily consist of mineral soils it is considered too weak to conclude the general validity of the Bjerrum curve in relation to gyttja, based on only the two data points from the test sites from Randers and Vejle.

The basis for the present reduction factor μ in the SGI approach was originally including Scandinavian organic soils. The right plot on figure 4 shows the test results from Randers and Vejle against the liquidity index, w_L including the data collected by L. Bjerrum recalculated by L. Andréasson [18] and by R. Larsson [9]. The reduction factor proposed by SGI seems to yield less scatter of the (Bjerrum) data - probably and partly due to the fact, that the estimation domain includes uncertainty only in w_L as opposed to PI (w_P and w_L) or that w_L is closer related to the in situ strength. Even though the oedometer tests from Randers and Vejle indicate OCR up to 2 the SGI approach seems conservative relative to the present test results, underestimating μ by at least 0.14 and 0.24 at Randers and Vejle, respectively. Considering the existing data from mineral soils and organic soils the SGI approach generally seems fair. Most organic postglacial soil in Denmark is normally to slightly preconsolidated (OCR < 2) but it does seldomly appears over consolidated (OCR > 5) when performing laboratory tests.

Laboratory tests

Oedometer tests (IL), triaxial tests (compression and extension) and direct simple shear tests (DSS) were performed on samples of gyttja from the Randers test site. While only oedometer tests (CRS) were performed on gyttja from the Vejle test site. Based on the test results the samples are considered disturbed to varying degree and hence do not yield a reliable estimate of the undrained shear strength. This is confirmed when comparing the results of the strength tests to the plate load tests ($c_{\text{u.laboratory}} < 0.5\ c_{\text{u.PLT}}$). When samples are recovered from a soft clay deposit they are always disturbed even with perfect sampling and results in a loss of shear strength of up to 10% [19]. These considerations do probably advocate for an inappropriate correlation of field vane strengths against results of laboratory undrained strength tests on gyttja and very soft clay where perfect sampling is considered quite a challenge. The gyttja samples at Randers and Vejle were recovered using a 76 mm steel tube sampler. Several authors have found sampling diameter to significantly impact the laboratory strength and deformation results in soft soils [20] and D.W. Hight a nd S. Leroueil recommend using large diameter (200 mm) thin walled open sampler to minimise the disturbance in soft soil [21].

5. DISCUSSION

Field vane correction factors

The present plate load test results indicate that the μ curve suggested by Bjerrum underestimates μ for gyttja, though the dependency on *PI* appears plausible. The data volume (two data points) is not considered sufficient for suggesting a less conservative approach to estimate μ for gyttja and organic soils – but the indications suggest further collection of data using the same approach (plate load tests).

As mentioned, one apparent advantage of the SGI approach over the Bjerrum approach is that the basis for the curves includes Scandinavian organic soils and gyttja. Although Bjerrum's original data, when plotted against the liquid limit (w_L) as shown on the right side of figure 4, exhibit less scatter around the SGI curve, the dataset from Larsson [9], which includes organic clay and gyttja, appears to result in greater scatter. This dataset is derived from laboratory tests and back-calculations based on full-scale failures. It is unclear which data points originate from laboratory tests and which are from back-calculations. However, it seems reasonable to speculate that the observed scatter may be attributed to variations in sample quality and disturbance associated with the laboratory tests or related to assumptions regarding the failure surface as discussed in the later sections. This indication is supported by the apparently significant underestimation of μ based on the results from the present study – though only two data points are available.

Assuming most gyttja to be normally to slightly preconsolidated, the dependence of *OCR* on μ using the SGI approach appears negligible, compared to the relative underestimation of μ given the present test results from Randers and Vejle. Due to the soft response and low strength, often observed for gyttja and high plasticity organic clay, assessing the preconsolidation stress, σ_{pc}, involves significant uncertainty. Generally, models should aim for simplicity as the introduction of each variable add a source of uncertainty and from a practical viewpoint, field vane tests are often not accompanied by consolidation tests. Considering this idea, the correction factor for gyttja might as well be assessed by the relation proposed by [9]

$$\mu = \left(\frac{0.43}{w_L}\right)^{0.45} \tag{6}$$

eliminating the dependence of *OCR*. Equation (6) is plotted on figure 4 and falls in the intermediate region of *OCR* = 1 to 2.

Plate load tests

Plate load tests were considered ideal for the present purpose of inferring the mean undrained shear strength for the evaluation of field vane correction factors for gyttja and organic clay. Even though plate load tests ideally eliminate the issue of sample disturbance it is challenging to prepare the ground level without disturbing the ground at all – even with great care. The stress conditions are not known but for the present purpose of comparing field vane tests to the average undrained shear strength under the same conditions this is considered irrelevant.

Field vane tests

The field vane tests used for the present study were performed in accordance with the guidelines provided by the Danish Geotechnical Society [3]. The Danish guidelines for performing field vane tests allow for a more rapid execution (≤ 1 rpm) compared to most international guidelines [2]. As the strain rate affects c_{fv} (or c_u), yielding a higher c_{fv} with increasing strain rate, the more rapid Danish approach is considered conservative in the current context, yielding a lower μ factor. The scatter in the field vane tests performed for the present study account for the majority of the uncert ainty in the estimation of μ. As the plate load test results were rather uniform, the scatter in the field vane test results are attributed to measurement error rather than natural variability in the undrained shear strength.

Even though the gyttja at the test locations in Randers and Vejle was considered rather clean (absence of coarse-grained soils) intact shell fragments were observed at both test sites. The appearance of shell fragments in marine soil deposits are rather common and can lead to variations in the field vane strength not reflecting the actual variability in the undrained shear strength or measurement error.

Back-calculation of undrained shear strength

The field vane correction factors established by L. Bjerrum were inferred from the back-calculation of actual full-scale failures and some plate load tests [15]. It is not clear but given the years of publication (1972 and 1973) and the indications in [4] and [15] circular failure surfaces seems to be assumed for the various analyses. Even though the basis for the field vane correction factors established and developed by SGI (right hand side of figure 4) include back-calculation of full scale failures gyttja – these probably also were based on circular failure surfaces, assuming the year of publication (1990). Circular failure surfaces are theoretically valid only for (fairly) homogenous soil conditions. As the (undrained) shear strength is always controlled by effective stresses, it is commonly accepted and observed that the ratio c_u/σ'_v is constant for normally consolidated soils, where σ'_v is the vertical effective stress at the depth considered. A. Skempton [22] found the ratio was dependent on the plasticity index, typically ranging from 0.1 to 0.4 [23]. If the ratio, defined as the initial undrained shear strength to the strength increase with depth, is sufficiently high, the failure surface tends to be located closer to the surface and exhibits a more elongated shape [7], contrasting with the typically observed circular failure surface when using a constant c_u – a tendency diminishing with increasing overall soil strength. It is important to recognize that the inference of c_u by back-calculation is contingent on the length of the failure surface; thus, a reliable estimation of the mean of c_u critically depends on the assumed shape of the failure surface.

Although the back-calculation of the average c_u from full-scale failures is deemed reliable and less susceptible to local variations in c_u along the failure surface and eliminates scaling issues, the average c_u derived from plate load test theoretically is less sensitive to increasing strength with depth. This is particularly notable in soft soils characterized by a high relative strength increase. Theoretically, the failure surface in plate load tests extends only about one plate radius beneath the plate [24]. Furthermore, the plate load test method eliminates the need for adjusting the results for end effects as pointed out by [25] who adjusted the results originally published by Bjerrum [4] and [15] to account for end effects.

Despite the abovementioned advantages of the plate load test for the assessment of c_u in soft soils, the inference of maximum applied stress, q_{max}, can be discussed when the load-deformation curves from the tests show no clear failure plateau - so can the applicability of the bearing capacity factors and shape factors derived for stiff soils under the assumption of fully developed failure surface. It can also be discussed whether the assessment of c_u at a displacement ratio, $r_\delta \approx 10\%$ (76 mm) or more is practically acceptable for conventional geotechnical structures – i.e. foundations – and the superstructures or interacting elements.

6. CONCLUSIONS

Based on results from plate load tests on gyttja, the field vane correction factors proposed by L. Bjerrum and the Swedish Geotechnical Institute (SGI) appear to be a conservative estimate for gyttja and organic clay, but further testing using the plate load test method is needed for confirming the present indications.

Due to inevitable sample disturbance laboratory tests are not recommended for assessing the validity of the field vane correction factors.

The field vane correction factor by Bjerrum seems to be conservative for gyttja and less conservative than the approach suggested by SGI. The strength of the SGI is the one parameter domain (w_L) - if the OCR is eliminated - resulting in less scatter than that of Bjerrum.

Caution is advised when inferring undrained shear strength from full-scale failures in low-strength soils that exhibit a significant increase in strength with depth, such as normally consolidated gyttja. A relatively high increase of strength with depth will often lead to a more critical failure surface than assuming constant c_u with depth. Some literature have apparent assessed the undrained shear strength by back-calculating full scale failures in gyttja assuming a circular failure surface – a natural assumption considering the tools available at the time of publication. Further research could involve recalculating the full-scale failures using more contemporary methods that allow for variations in undrained shear strength with depth and do not presuppose a fixed mode of failure.

ACKNOWLEDGEMENT

The present research has been funded by COWIfonden and Ellen og Ove Arkils fond. The authors would like to thank Rødkilde Gymnasium for making available the test site in Vejle. Furthermore, we would acknowledge students Camilla Hesel, Gustav Krogh and Mads Roholm from Aarhus University involved in the execution of the plate load tests in Randers. Finally, we would like to thank Arkil and Svend Jørgensen for the great collaboration and discussions on execution etc.

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