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Title of Paper: Evaluation of Peat Strength for Stability Assessments

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Synopsis

In this paper guidance is given for the assessment of peat strength for stability assessments based on laboratory undrained simple shear tests (SS). When considering the stability of peat, these tests will yield a conservative estimation of the in-situ strength of the peat mass. The study was motivated by recent interest in renewable energy developments in upland peat areas. The results of more than 111 SS tests from 16 sites in Ireland, Scotland and the Netherlands were studied. It was found that peat strength is strongly influenced by its stress history and also varies as a function of the water content and degree of decomposition (fibre content). The normally consolidated normalised strength ratio (s_u/σ_v') from SS tests of peat was found to be approximately 0.4, which is towards the lower bound of previously published data for peat. Comparisons of strengths derived from SS and field vane tests showed the ratio of the strength derived from the two tests was influenced by the degree of decomposition and that previously published correction factors for field vane strengths are inappropriate. Guidance is given for engineers working on future schemes on upland peat areas.

Key words: Peat, Site investigation, Strength and Testing of Material;

Notation:

s_u = undrained shear strength (s_{u-SS} from simple shear test, s_{u-FV} from field vane, s_{u-TC} from triaxial compression test)

z = depth of failure surface

β = slope angle on base of sliding

γ_b = bulk unit weight

γ = shear strain

$\mu_{\text{FV-C}}$ = field vane correction factor

σ_v' = vertical effective stress (σ'_{v0} = in situ, σ'_{vc} = consolidation)

Introduction

The growth of renewable energy developments in recent years, especially for wind energy but also for pumped storage schemes, has led to an increased level of development in upland environments. There has been particular interest in Ireland and the United Kingdom. To capture the optimum wind resource in a particular area, these developments often take place on hills and mountains, which in the British Isles can often have peat or strongly organic soils at the surface, particularly in the wetter regions. Roads, flood defences, housing, small scale developments in lowland areas may also encounter peat deposits. Peat, which forms from the accumulation of organic material over thousands of years, is characterised by its high water content and compressibility and low shear stiffness and shear strength. This soil is often classed as problematic due to the large settlements observed under relatively low loads, long term creep settlements and low bearing capacity for structures founded on it. The potential for peat slides / flows that may occur naturally or be triggered by human activity further strengthens this negative outlook. While the occurrence of peat slides / flows is not a recent phenomenon, the need to develop infrastructure in these environments has brought about increased awareness of this geohazard. A number of significant peat slides / flows have been recorded since 2003 (Dykes and Warburton, 2007; Dykes and Warburton, 2008; Long and Jennings, 2006;

Long et al., 2011), some of which occurred alongside engineering works. These have put emphasis on the need to consider peat stability during development of upland areas.

The task of assessing the stability of peat deposits is not a straightforward one, particularly due to the wide range of causal factors that have been noted to play a role in peat slides / flows and also due to the poor understanding of this material. Extreme rainfall events or periods of prolonged antecedent rainfall are the most common factors in the occurrence of peat slides/flows. The failures that occurred at Pollatomish, Co. Mayo (Long and Jennings, 2006) and on the Shetland Islands (Dykes and Warburton, 2008) on the same night in September 2003, were triggered by extreme rainfall events and the majority of failures have been noted to occur in the wetter autumn and winter months (Alexander et al., 1985). Slides/flows of peat have also been initiated from bearing type failures after the peat surface has been loaded. This was identified as a factor in the failure near Derrybrien, Co. Galway in 2003 (AGEC, 2004). At this event, the placement of a relatively small load on the peat surface led to a failure involving 450,000m³ of peat. Cuttings in peat for drainage (Tomlinson, 1981) and excavations of peat for fuel (Praeger, 1897) have also been noted as trigger factors for large scale failures. In the latter example, eight people were killed when the 3 m high cutting gave way after a heavy rainfall event. While many failures can be linked to external trigger factors, causal factors linked to the morphology of the peat, the presence of preferential hydrological pathways or pipes in the peat, and the interaction with the underlying soil have been noted as playing a role in these events (Boylan et al., 2008).

Compared to mineral soils such as clays and sands, assessment of the geotechnical properties of peat is complicated by its high water content and compressibility, and organic composition. The high compressibility of peat and the need to break fibres during sampling makes obtaining high quality samples difficult and disturbed samples may display non-conservative parameters for stability assessments (i.e. increased strength). The difficulties with obtaining samples for laboratory tests often makes in-situ assessment of peat strength a more favourable option in practice, with the field vane test being the most commonly used test to obtain strength parameters. However, vane testing has been noted by many researchers to be inappropriate for peat, possibly leading to non-conservative strength parameters for stability assessments (Landva, 1980; Long and Boylan, 2008). Few studies have been carried out using simple shear (SS) testing of peat, which would provide strength parameters more appropriate for stability analyses of translational type, which peat slope failures often resemble. Indeed, back-analysis of the failure of a trial embankment constructed on peat in the Netherlands (Zwanenburg et al., 2012), where the observed failure was translational, showed that the failure corresponded closest with parameters determined from SS tests. Although traditionally effective stress strength parameters have mostly been used to analyse embankments on organic soils in the Netherlands, consideration has recently been given to the use of undrained strengths from SS tests (Den Haan and Feddema, 2012).

This paper describes the results of a study carried out to examine the undrained shear strength of peat using the Simple Shear (SS) apparatus (also referred to as the Direct Simple Shear (DSS) apparatus). Tests were conducted on peat samples from 16 sites in

Ireland, Scotland and the Netherlands, that cover a range of peat of varying levels of decomposition. In-situ vane tests were carried out at a number of the sites and the results of these are compared to the strengths obtained in the laboratory. The trends observed for both the laboratory and in-situ tests are discussed and recommendations are made for determining the shear strength of peat in practice.

Stability Assessments of Peat Deposits

Given the wide range of causal factors, assessments of the stability of peat adjacent to engineering works often involve a combination of qualitative risk assessments (QRA) to rank various zones within a site and engineering stability assessments to assess the factor of safety of particular locations against failure. To determine the stability of a deposit, having determined the slope angle, an important task is to identify the drainage conditions that dictate the soil behaviour during a particular failure scenario. However, from an examination of the range of causal factors of peat failures reported in the literature, it could be argued that the soil behaviour during a peat failure could range from undrained (e.g. sudden loading, short duration extreme rainfall event etc.) to drained (e.g. drying and cracking of peat during summer, creep of peat at a significant change in the slope angle etc.). The range of permeability values reported for peat and its potential to change significantly under modest loading (Hanrahan, 1954; Mesri and Ajlouni, 2007) adds further uncertainty to the appropriate drainage conditions to consider. To the authors' knowledge, owing to the possibility that the drainage condition could vary from fully undrained to fully drained, engineers often undertake an undrained stability assessment which represents the more conservative approach.

As peat slope failures for the most part resemble planar translational slides (Dykes and Kirk, 2001; Hendrick, 1990; Long and Jennings, 2006; Warburton et al., 2003), these stability assessments are generally undertaken using relatively simple infinite slope analysis approaches. According to Haefli (1948) and subsequently Skempton and DeLory (1957), the factor of safety, FOS, for a planar translation slide, if the peat is assumed to behave in an undrained manner is given by Equation 1.

$$FOS = \frac{s_u}{\gamma_b z \sin \beta \cos \beta} \quad [1]$$

where s_u = undrained shear strength of peat, γ_b = bulk unit weight, β = slope angle on base of sliding and z = depth of failure surface. For these assessments, the greatest uncertainty surrounds the value of the undrained shear strength to be used.

Shear Strength of Peat

In-situ Testing

The field vane test (FVT) is the most frequently used device in the UK and Ireland to obtain “undrained” strength parameters (s_{u-FV}) for peat deposits. This is despite known problems with the test in peat which leads to questionable results. In a comprehensive review of the vane test in peat, Landva (1980) observed that a void was generated behind the blade into which the compressed peat in front of the blade drained resulting in a modified peat. This would lead to strength parameters that are higher than the truly undrained strength due to the partial drainage effects. Landva (1980) and Helenelund (1967) also reported that a cylindrical shear surface occurred at a diameter 7 mm to 10 mm outside the edge of the blade and the length of the vane shear face was shorter due to the compression / void mechanism described above. Therefore the assumed failure

surface, from which s_{u-FV} is calculated, is quite different to the actual failure surface. In fibrous peat, fibres often wrap around the vane during rotation and increase the resistance being measured. Figure 1 shows an example of a typical variation in shear strength measured during rotation in fibrous peat. After the peak strength was reached, the shear strength drops suddenly and the sound of fibres tearing was heard. The influence of the fibres on the peak shear strength and whether their interaction with the vane results in a strength that is different to the mobilised strength during other modes of failure is extremely difficult to quantify. .

Unlike mineral soils, s_{u-FV} in peat has been found to decrease with increasing vane diameter, possibly due to the effect of the fibres and the scale effect of these. Landva (1980) concluded that the field vane test is “of little engineering value in fibrous material” and is also not suitable for organic soils. Helenelund (1967) similarly concluded that the “test is not reliable in fibrous peat”. To overcome these difficulties, Edil (2001) suggested a vane correction factor, $\mu_{FV-C} = 0.4 - 0.5$, while Mesri and Ajlouni (2007) suggested a correction factor, $\mu_{FV-C} = 0.5$ be applied to the results of vane tests in peat. Despite all the issues identified with vane tests in peat, it continues to be the most common used test to determine the shear strength of peat.

Laboratory Testing

Laboratory testing of peat specimens is carried out to a lesser degree than in-situ tests, largely due to difficulties handling and preparing samples as well as problems achieving the appropriate stress levels to replicate in-situ conditions in standard laboratory apparatus. Laboratory testing of peat has mainly been carried out using triaxial

compression tests, while simple shear tests have also been carried out in a limited number of cases. Long (2005) reviewed some of the issues related to carrying out triaxial tests on peat, particularly at low effective stresses. End platen roughness and corrections for membrane resistance were highlighted as important areas to be considered when testing peat. Pressure controllers used to apply the stresses to the specimen are only accurate to ± 2 kPa and it is suggested to use a differential pressure transducer to ensure that the differential pressure between the cell and back pressure controlling devices is constant. De Jong (2007), studying the stability of peat dykes, noted the unsuitability of standard SS apparatus to test peat at the low effective stress levels encountered in situ. Standard SS equipment may have difficulty consolidating to low stresses (< 5 kPa).

Published data for laboratory tests on peat indicates that peat and organic soils have large normalised undrained strength ratios (s_u/σ'_v) which are higher than that of normally consolidated mineral soils. Figure 2 shows a summary from published literature of the normalised strengths of peat versus organic content (OC) for (a) triaxial compression tests, and (b) simple shear tests. For triaxial compression, s_{u-TC}/σ'_v values range from 0.47 to 0.75 for peat (OC $> 80\%$). This is compared to the typical range of 0.3 to 0.35 for a normally consolidated clay or silt (Ladd, 1991). For SS tests, s_{u-SS}/σ'_v values vary from 0.38 to 0.55, with one point lying outside this range. For a normally consolidated clay or silt, the range would be between 0.2 to 0.27 (Ladd, 1991). It is not clear from all of the publications listed in Figure 2, whether the specimens are normally consolidated or have been subjected to a stress history that has increased their normalised strength ratios.

Nonetheless it is clear that the range of s_u/σ_v' values for peat is consistently higher than for normally consolidated clays and silts.

Research Sites & Testing

Overview of Sites

The research described in this paper was carried out at 16 sites in Ireland, Scotland and the Netherlands. Table 1 provides a summary of the sites, basic properties of the peat, the sampling method employed and whether any field vane tests were carried out. Thirteen of the sites are located in Ireland, two are in the Netherlands and one is in Scotland (shown on the map in Figure 3) and were investigated as part of ongoing research at University College Dublin (UCD) on the shear strength of peat. The two sites in the Netherlands were investigated as part of a joint UCD / TU Delft research project, which is described elsewhere (Boylan et al., 2011; Mathijssen et al., 2008)

Sampling techniques varied from site to site and the specific technique used depended on resources available, the conditions of the site and health and safety considerations. For instance, hand carving of block samples was only carried out at shallow depths where there is minimal risk to sampling personnel from collapse of the excavation. Sampling was carried, by hand carving blocks and by machine or hand pushing various sampling tubes with either a plain or serrated edge. The SGI (SGI) sampler, as described by Carlsten (1988), is an example of such a sampler with a serrated cutting edge. It is of 100 mm diameter and contains an optional core catcher. The cutting head is attached to a plastic tube and the sampler is pushed / rotated into the ground. Additionally the high

quality Sherbrooke block sampler, which is described by Lefebvre and Poulin (1979), was used at the two sites in the Netherlands.

Generally, the samples were obtained from relatively shallow depths between 1 m and 2.5 m, although samples were obtained from greater depths at a small number of sites where the peat is deeper. The peat obtained from sites in Ireland generally have very high water content, usually of the order of 1000% and had a large variation in degree of decomposition with von Post H between 2 and 9 (von Post and Granlund, 1926). The peat from the two sites in the Netherlands has lower water content but similar range of degree of decomposition to the Irish sites.

Simple Shear Testing

Simple Shear (SS) testing was carried out on 111 specimens from the research sites. These tests were carried out two SS apparatuses, a specially designed apparatus for testing peat at low effective stresses called the UCD-DSS apparatus (Boylan and Long, 2009) and a Geonor H-12 DSS apparatus (Bjerrum and Landva, 1966). Modifications were made to the latter apparatus to improve its capability to consolidate to low effective stresses (< 10 kPa).

Undrained SS tests were conducted in both apparatus as constant volume tests where the height of the specimen is held constant throughout the shearing stage of the test. For a fully saturated sample, the change in vertical stress during shear to maintain the constant height is assumed to equal the change in pore water pressure which would take place in a truly undrained test. Dyvik et al. (1987) confirmed this assumption in a comprehensive

study of constant volume SS tests and truly undrained SS tests on normally consolidated Drammen clay.

Prior to shearing, test specimens were consolidated to either an estimate of the in-situ vertical effective stress (σ'_{v0}) or an arbitrary large stress (expected to be higher than previous stresses applied to the specimen). While the former tests were consolidated to the in-situ effective stress, the shear strength behaviour would be a function of the stress history of the specimen. The latter tests were therefore carried out on specimens from specific sites to examine the behaviour of the peat under close to normally consolidated conditions. Samples were consolidated in several steps to the required consolidation stress (σ'_{vc}) and then left overnight. The following day the specimens were sheared at a constant shear strain (γ) rate of 4% per hour. In order to maintain constant volume conditions, the vertical displacement of the top cap was monitored throughout and adjustments made to the vertical stress to maintain the constant height of the specimen.

The results of each test were corrected for compliance (generally less than 0.5 kPa) due to membrane stiffness and apparatus friction. The undrained shear strength (s_{u-SS}) is taken to be equal to the peak horizontal shear stress attained during shearing or alternatively the shear stress measured at 15% shear strain, whichever occurs first.

In-situ Vane Testing

Vane tests were carried out using both a GEONOR H-10 apparatus (vane height / diameter = 110 / 55 mm) and a GEOTECH Electrical Vane (both 280 / 140 mm and 172 / 80 mm vanes used). The former is a hand operated device while the latter is mounted on a

standalone unit and is driven by a computer controlled motor. All tests were conducted at a rate of approximately 1° per second.

Results

General Trends

Figure 4 summarises the results from all of the SS tests, grouped by site number (given in Table 1), shown in terms of the undrained shear strength (s_{u-SS}) versus the consolidation stress. As expected shear strength increases as a function of the consolidation stress.

In Figure 5a the shear strengths have been normalised by the consolidation stress resulting in the normalised shear strengths (s_u/σ'_{vc}). Values of s_u/σ'_{vc} range from 0.25 to 1.35 across all of the sites. In Figure 5b the tests results are grouped by those that were carried out following consolidation to the in-situ effective stress (σ'_{v0}) and those carried out to arbitrary stresses. The tests carried out on specimens consolidated to 'In-situ Stress' are grouped close together as the arbitrary stresses were generally chosen to be far greater than the in-situ effective stress at each site. For the 'In-situ Stress' group, s_u/σ'_{vc} ranges from 0.4 to 1.35, while for the 'Arbitrary Stress' group s_u/σ'_{vc} values range from 0.25 to 0.9 with a near uniform value of ~ 0.4 for consolidation stresses greater than 30 kPa.

The difference between the two sets of data arises due to the different stress histories of the specimens. For the tests carried out to in-situ effective stresses, the specimens may be overconsolidated to some degree, as the past maximum applied stress (e.g. due to overburden that has been removed or frequent changes in the water table) may be greater

than the in-situ effective stress, and therefore the shear strength will be a function of the in-situ stress history. For the specimens that have been consolidated to arbitrary stresses, the consolidation stresses have been chosen to be many multiples of the in-situ stresses with the aim of exceeding the past maximum applied stress. Therefore the near uniform s_u/σ'_{vc} value of ~ 0.4 at large consolidation stresses represents conditions closer to normal consolidation conditions where the consolidation stress is greater than all previous stresses applied to the specimen. This value lies towards the lower bound of the published data give in Figure 2, suggesting that the scatter in the data from published literature may arise, in part, due to the stress history of the specimens.

Relationship with Basic Parameters

The water content of peat is sometimes used in practice to give an indication of the shear strength when laboratory or in-situ measures of strength are not available. Figure 6 shows the variation of shear strength with the water content of the specimens after consolidation. As expected, there is a general trend of decreasing shear strength with increasing water content. The bounds of the empirical correlation between vane shear strengths (s_{u-FV}) and water content suggested by Amaryan et al. (1973) are also shown. While the majority of the data falls within the bounds, a significant portion falls below the lower bound. The wide range of these empirical bounds makes them of little use for stability assessments where an accurate and conservative strength is preferable.

Figure 7 shows the variation of s_{u-SS}/σ'_{vc} versus the level of decomposition. Note that the results are only shown for tests carried out at arbitrary stresses as no trends were observed in the full data set due to effects of stress history. Although there is much

scatter in the data, there appears to be reduced variation of s_{u-SS}/σ'_{vc} with increasing decomposition. All of the peat studied here, even that at maximum degree of decomposition, contained fibres. Nevertheless, as the presence of fibres, and in particular the intactness of the fibre, reduces with increasing decomposition, this observation highlights that fibres may contribute to the variability of measured peat strengths, particularly at low degrees of decomposition.

Comparison of In-Situ Vane and Laboratory Strength

In-situ vane tests were carried out at 8 of the sites given in Table 1. Figure 8 shows an example of the shear strengths measured at the Loughrea site (Site 14 in Table 1 and Figure 3). At this location, the water content of the peat varies from 900% to 1600% and the level of decomposition ranges from H4 to H7. Within the 2 m depth interval, vane strengths range from 6.1 to 9.7 kPa. In contrast the shear strengths measured in SS tests resulted in s_{u-SS} values ranging from 2.5 to 3 kPa. The ratio of vane to SS strength (s_{u-vane}/s_{u-SS}) ranges from 3 to 4 at the depths where both tests were carried out.

Figure 9a shows the normalised strengths for all the vane tests with depth. Figure 9b shows a close-up of the normalised vane strengths less than 2.0. Above 2 m, the normalised strength from all the sites range from about 0.8 to 9.0. This wide range of values reflects the low degree of decomposition (i.e. fibrous peat) that is generally found close to the surface of peat sites. In addition, the peat closest the surface would have experienced higher levels of stress due to surface loadings and seasonal fluctuations of the water table, thus resulting in more overconsolidated peat compared to peat at depth. At depth, the normalised strengths occupy a narrower range of values from 0.7 to 3.5,

reflecting a reduction in overconsolidation ratio with depth and possibly lower levels of fibres found in the more decomposed peat. Compared to the range of normalised strengths observed in the laboratory, the lower bound value from the vane tests is 1.75 times greater than the normally consolidated s_{u-SS}/σ'_{vc} of 0.4.

To further investigate the range of strengths measured from in-situ vane tests the ratio s_{u-vane}/s_{u-SS} versus degree of decomposition, H, for depths at which vane tests and SS tests exist at the research sites are compared on Figure 10. For this comparison, the 36 tests range in decomposition from H4 to H9, which covers a range of moderately to well decomposed peat. The ratio of s_{u-vane}/s_{u-SS} ranges from 1 to 5.7, with the highest ratios observed for lower values of decomposition. The higher ratios for the lower levels of decomposition is likely due to the greater influence of fibres on the vane compared to the more decomposed peat where fibres have decomposed. In addition, the effect of partial drainage of the peat being sheared by the vane would have played a more significant role in tests conducted in peat of low decomposition and hence more permeable than peat of a higher degree of decomposition. The wide variation of ratios and the high values, far greater than 1, suggests that in-situ vane tests may grossly overestimate the shear strength of peat deposits. Considering the s_{u-vane}/s_{u-SS} ratio of 2.0 implied by the vane correction factors suggested by Edil (2001) and Mesri and Ajlouni (2007), approximately 70% of the values lie above this level implying that a universal correction factor is insufficient for correcting vane tests in peat.

Summary

This paper describes a study of the shear strength of peat for stability assessments using the Simple Shear (SS) apparatus. The motivation of the study was to provide guidance to engineers designing infrastructure and assessing the stability of peat deposits. Tests were conducted on peat samples from 16 sites from Ireland, Scotland and the Netherlands and cover a range of peat of varying water content and degrees of decomposition. In-situ vane tests were carried out at a number of the sites and the results of these are compared to the strengths obtained in the laboratory. The main conclusions from this study are:

- The published literature shows much scatter in the range of normalised strength ratios (s_u/σ'_v) for peat. Trends observed in this study suggest this may be largely due to the effects of stress history.
- Based on the results presented in this paper, peat strength is shown to be significantly effected by stress history (either in the field or the laboratory), its water content and the degree of decomposition.
- For the sites examined, a lower bound normally consolidated strength ratio for peat (s_u/σ'_v) equal to 0.4 was obtained from SS testing. This coincides with the lower bound of the published data.
- The ratio between the shear strength measured in-situ using the vane apparatus and that obtained in the laboratory SS tests (s_{u-vane}/s_{u-SS}) ranges from 1 to 5.7, decreasing with increasing decomposition. These values are generally greater than the value of 2.0 that is implied by the vane correction factors suggested by Edil (2001) and Mesri and Ajlouni (2007). Thus vane tests in peat may give

misleading and non-conservative results for stability assessments and should be treated with great caution.

Advice for Practicing Engineers

The following approach is suggested for future investigations of upland peat sites:

- Initially probe the site using simple methods or ideally using ground penetrating radar (GPR) to determine the underlying morphology of the peat (Boylan and Long, 2012).
- Hand-sample the peat at regular intervals using a gouge auger or “Russian” peat sampler (Jowsey, 1966).
- Carry out a detailed logs of peat which should include full classification according to von Post and Granlund (1926). This classification should include details of the fine (F) and coarse (R) fibre content, the wood fraction (W), the tensile strength of the fibres (T), the plasticity (P) as well as the degree of decomposition (H). A laboratory water content (w) determination should also be made. This level of classification provides a detailed baseline of the peat properties that is helpful when interacting with other discipline (e.g. Engineering Geologists, Geomorphologists etc) that may provide input into Qualitative Risk Assessments (QRA).
- For stability assessments, conservatively assume that the peat will behave in an undrained manner in the field and estimate the strength assuming a conservative undrained strength ratio (s_u/σ'_v). Assumed values should be confirmed through laboratory testing.

- Identify the most vulnerable locations, sample the peat and carry out laboratory strength testing. If it is not possible to get block samples use a tube with serrated edges.
- Multiple tests should be carried out on peat at similar depths to assess the natural variability. It would be preferable to carry out SS testing, however in circumstances where this test method is not available, use of alternate test methods (e.g. triaxial compression) may be considered. However the strength anisotropy and the differing modes of shearing in the various laboratory test types needs to be taken into account when assessing strength parameters.

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Figure 1. Typical In-situ Vane test in Fibrous Peat Deposit

Figure 2. Summary of Laboratory Strengths of Peat (a) Triaxial compression (b) Simple shear

Figure 3. Site Locations in (a) Ireland, (b) Scotland and (c) the Netherlands

Figure 4. Results of Simple Shear (SS) tests

Figure 5. Normalised Simple Shear Strengths Organised by (a) Site (b) Stress Level

Figure 6. Variation of Simple Shear Strength with Water Content

Figure 7. Normalised Simple Shear Strengths versus Von Post Decomposition

Figure 8. Loughrea Site (a) Variation of Water Content and Degree of Decomposition with Depth (b) Comparison of Vane and Simple Shear

Figure 9. Normalised Strengths from in-situ vane tests with depth

Figure 10. Ratio of In-situ Vane Strength and Simple Shear Strength

Table 1. Summary of Research Sites

| Site Number | Site | Depth Range (m) | Water Content (%) | Degree of Decomposition¹, H | Sample type | Vane Testing | Reference |
|--------------------|-----------------------------|------------------------|--------------------------|-----------------------------------------------|----------------------|---------------------|------------------------------------------------|
| 1 | Annaholty, Ireland | 0.6 - 1 | 970 - 1120 | H4 | 100 mm piston | N | Boylan (2008) |
| 2 | Ballincollig Hill, Ireland | 0.8 - 2.5 | 530 - 1200 | H5 – H7 | 100 mm piston | N | Long et al. (2011) |
| 3 | Bodegraven, The Netherlands | 1.1 - 4.2 | 220 - 300 | H5 – H7 | Sherbrooke block | Y | Boylan et al. (2011); Mathijssen et al. (2008) |
| 4 | Camster, Scotland | 1.1 – 6.9 | 530 - 950 | H5 – H9 | Rotary | N | |
| 5 | Carn Park, Ireland | 0.5 - 2.0 | 720 - 1050 | H4 – H5 | Hand cut block | N | |
| 6 | Charlestown, Ireland | 0.9 – 1.2 | 860 - 1170 | H4 – H7 | 100 mm piston | N | Boylan (2008) |
| 7 | East Galway, Ireland | 1.8 - 5.9 | 510 - 1060 | H3 – H7 | 100 mm piston | Y | |
| 8 | Cloosh, Ireland | 0.1 – 2.5 | 570 - 1010 | H6 –H 9 | 100 mm piston | Y | |
| 9 | Crockagarron, Ireland | 0.9 – 2.5 | 790 - 1260 | H2 – H8 | Hand cut block / SGI | Y | |
| 10 | Garvagh Glebe, Ireland | 0.8 - 2.5 | 610 - 990 | H5 – H9 | Hand cut block / SGI | N | |
| 11 | Glencolumcille, Ireland | 0.5 - 1.5 | 770 - 1010 | H4 – H7 | Hand cut block | N | Long et al. (2011) |
| 12 | SW Donegal | 0.5 – 2.2 | 530 - 980 | H5 – H8 | 100 mm piston | Y | |
| 13 | Glinsk | 1.3 - 2.3 | 350 - 730 | H5 – H7 | 150 mm tube | Y | |
| 14 | Loughrea, Ireland, | 0.5 – 1 | 1060 - 1200 | H4 -H5 | 100 mm piston | Y | Boylan (2008) |
| 15 | Roosky, Ireland | 1.1 – 1.3 | 840 - 1120 | H4 -H5 | Hand cut block | N | |
| 16 | Vinkeveen, The Netherlands | 2 - 4.7 | 600 - 940 | H5 – H7 | Sherbrooke block | Y | Boylan et al. (2011); Mathijssen et al. (2008) |

¹ Degree of decomposition assessed according to the scale developed by Von Post and Granlund (1926) where H1 indicates no decomposition and H10 indicated complete decomposition of plant matter.

References on Figures only: (Carlsten, 2000)

References

- Adams, J.I., 1965. The engineering behaviour of a Canadian muskeg, Proc. 6th Int. Conf. Soil Mech. Found. Eng., Montreal, Canada, pp. 3-7.
- AGEC, 2004. Final Report on Derrybrien Wind Farm Post-Landslide Site Appraisal, Applied Ground Engineering Consultants.
- Ajlouni, M., 2000. Geotechnical properties of peat and related engineering problems. PhD Thesis Thesis, University of Illinois at Urbana-Champaign.
- Alexander, R., Coxon, P. and Thorn, R.T., 1985. Bog Flows in South-east Sligo and South-west Leitrim. IQUA Field Guide 8.
- Amaryan, L.S., Sorokina, G.V. and Ostoumova, L.V., 1973. Consolidation laws and mechanical-structural properties of peaty soils, Proc. 8th Int. Conf. Soil Mech. and Found. Eng., Moscow, pp. 1-6.
- Bjerrum, L. and Landva, A.O., 1966. Direct simple-shear tests on a Norwegian quick clay. *Géotechnique*, 16(1): 1-20.
- Boylan, N., 2008. The shear strength of peat. PhD Thesis, University College Dublin.
- Boylan, N., Jennings, P. and Long, M., 2008. Peat slope failure in Ireland Quarterly *Journal of Engineering Geology and Hydrogeology*, 41(1): 93-108.
- Boylan, N. and Long, M., 2009. Development of a direct simple shear apparatus for peat soils. *ASTM Geotechnical Testing Journal*, 32(2): 126-138.
- Boylan, N. and Long, M., 2012. In situ testing of peat – a review and update on recent developments. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, 43(No. 4, December).
- Boylan, N., Long, M. and Mathijssen, F.A.J.M., 2011. In situ strength characterisation of peat and organic soil using full-flow penetrometers. *Canadian Geotechnical Journal*, 48(7): 1085-1099.
- Carlsten, P., 1988. Geotechnical properties of peat and up-to-date methods for design and construction. *Varia No. 215*, Swedish Geotechnical Institute (SGI).
- Carlsten, P., 2000. Geotechnical properties of some Swedish peats, 13th NGM - 2000, *Nordiska Geoteknikermötet*, Helsinki, pp. 51-60.
- De Jong, A.K., 2007. Modelling peat dike stability. Masters thesis Thesis, TU Delft.
- Den Haan, E.J. and Feddema, A., 2012. Deformation and strength of embankments on soft Dutch soil. *Proceedings Institution of Civil Engineers, Geotechnical Engineering*, <http://dx.doi.org/10.1680/geng.9.00086>.
- Dhowian, A.W., 1978. Consolidation effects on properties of highly compressive soils-peats. PhD Thesis Thesis, University of Wisconsin-Madison.
- Dykes, A.P. and Kirk, K.J., 2001. Initiation of a multiple peat slide on Cuilcagh Mountain, Northern Ireland. *Earth Surface Processes and Landforms*, 26: 395-408.
- Dykes, A.P. and Warburton, J., 2007. Significance of geomorphological and subsurface drainage controls on failures of peat-covered hill slopes triggered by extreme rainfall. *Earth Surface Processes and Landforms*, 32(12): 1841-1862.

- Dykes, A.P. and Warburton, J., 2008. Characteristics of the Shetland Islands (UK) peat slides of 19 September 2003, *Landslides*.
- Dyvik, R., Berre, T., Lacasse, S. and Raadim, B., 1987. Comparison of truly undrained and constant volume direct simple shear tests. *Géotechnique*, 37(1): 3-10.
- Edil, T.B., 2001. Site characterisation in peat and organic soils, *Proc. Int. Conf. on In Situ Measurement of Soil Properties and Case Histories*, Bali, Indonesia, pp. 49-59.
- Edil, T.B. and Wang, X., 2000. Shear strength and K_0 of peats and organic soils, *Geotechnics of High Water Content Materials*. ASTM STP 1374, Memphis, Tennessee, pp. 209-225.
- Farrell, E.R. and Hebib, S., 1998. The determination of the geotechnical parameters of organic soils, *Proceedings of International Symposium on Problematic Soils, IS-TOHOKU 98*, Sendai, Japan, pp. 33-36.
- Farrell, E.R., Jonker, S.K., Knibbeler, A.G.M. and Brinkgrieve, R.B.J., 1999. Use of direct simple shear test for the design of a motorway on peat, *Proc. 12th European Conference on Soil Mechanics and Geotechnical Engineering*, Amsterdam, pp. 1027-1033.
- Foott, R. and Ladd, C.C., 1981. Undrained settlement of plastic and organic clays. *Journal of Geotechnical Engineering Division ASCE*, 107(8): 1079-1094.
- Haefli, R., 1948. The stability of slopes acted on by parallel seepages, *Proc. 2nd ICFSMFE*, pp. 134-148.
- Hanrahan, E.T., 1954. An investigation of physical properties of peat. *Géotechnique*, 4(3): 108-121.
- Helenelund, K.V., 1967. Vane tests and tension tests on fibrous peats, *Proc. Geotech. Conf. on shear strength properties of natural soils and rocks*, Oslo, pp. 199-203.
- Hendrick, E., 1990. A Bog Flow at Bellacorrick Forest, Co. Mayo. *Irish Forestry*, 47(1): 32-44.
- Jowsey, P.C., 1966. An improved peat sampler. *New Phytologist*, 65: 245-248.
- Ladd, C.C., 1991. Stability evaluation during staged construction. *Journal of Geotechnical Engineering Division ASCE*, 117(4): 540-615.
- Landva, A.O., 1980. Vane testing in peat. *Canadian Geotechnical Journal*, 17(1): 1-19.
- Lechowicz, Z., 1994. An evaluation of the increase in shear strength of organic soils, *Advances in the Understanding and Modelling the Mechanical Behaviour of Peat*. Balkema, Rotterdam, pp. 167-180.
- Lefebvre, G. and Poulin, C., 1979. A new method of sampling in sensitive clay. *Canadian Geotechnical Journal*, 16(1): 226-233.
- Long, M., 2005. Review of peat strength, peat characterisation and constitutive modelling of peat with reference to landslides. *Studia Geotechnica et Mechanica*, 27: 67-90.
- Long, M. and Boylan, N., 2008. Discussion on Nichol et al. (2007): A5 Llyn Ogwen peat slide, Capel Curig, North Wales. *Quarterly Journal of Engineering Geology and Hydrogeology (QJEGH)*, 41(November): 487 - 489.
- Long, M. and Jennings, P., 2006. Analysis of the peat slide at Pollatomish, Co. Mayo, Ireland. *Landslides*, 3(1): 51-61.
- Long, M., Jennings, P. and Carroll, R., 2011. Irish peat slides 2006 - 2010. *Landslides*, 8(3): 391 - 401.

- Mathijssen, F.A.J.M., Boylan, N., Long, M. and Molenkamp, F., 2008. Sample disturbance of organic soils. In: A.B. Huang and P.W. Mayne (Editors), Proceedings of 3rd International Conf. on Geotechnical and Geophysical Site Characterization - ISC'3. Taylor and Francis, Taipei, pp. 1481 - 1488.
- Mesri, G. and Ajlouni, M., 2007. Engineering properties of fibrous peats. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 133(7): 850-866.
- Praeger, R.L., 1897. Bog bursts, with special reference to the recent disaster in Co. Kerry. *Irish Naturalist*, 6: 141-162.
- SGI, 1946. (Swedish Geotechnical Institute) Korfattat compedium i geoteknikk Meddelande Nr. 1 (in Swedish), Stockholm.
- Skempton, A.W. and De Lory, F.A., 1957. Stability of natural slopes in London Clay, Proc. 4th ICSMFE, Rotterdam, pp. 72-78.
- Tomlinson, R.W., 1981. A preliminary note on the bog-burst at Carrowmaculla, Co. Fermanagh, November 1979. *Irish Naturalists Journal*, 20: 313-316.
- von Post, L. and Granlund, E., 1926. Peat resources in southern Sweden. *Sveriges geologiska undersökning, Yearbook*, 335(19.2 Series C): 1 – 127.
- Warburton, J., Higgitt, D. and Mills, A.J., 2003. Anatomy of a Pennine Peat Slide, Northern England. *Earth Surface Processes and Landforms*, 28(5): 457-473.
- Zwanenburg, C., Den Haan, E.J., Kruse, G.A.M. and Koelewijn, A.R., 2012. Failure of a trial embankment on peat in Booneschans, the Netherlands. *Géotechnique*, 62(5): 479 - 490.

Figures for Boylan and Long on Evaluation of peat strength for stability assessments

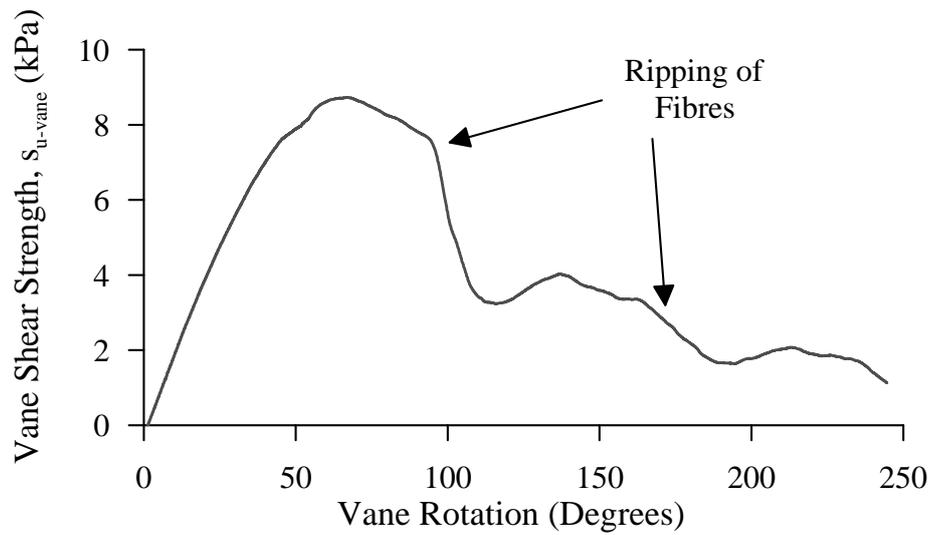


Figure 1. Typical in-situ vane test in fibrous peat deposit

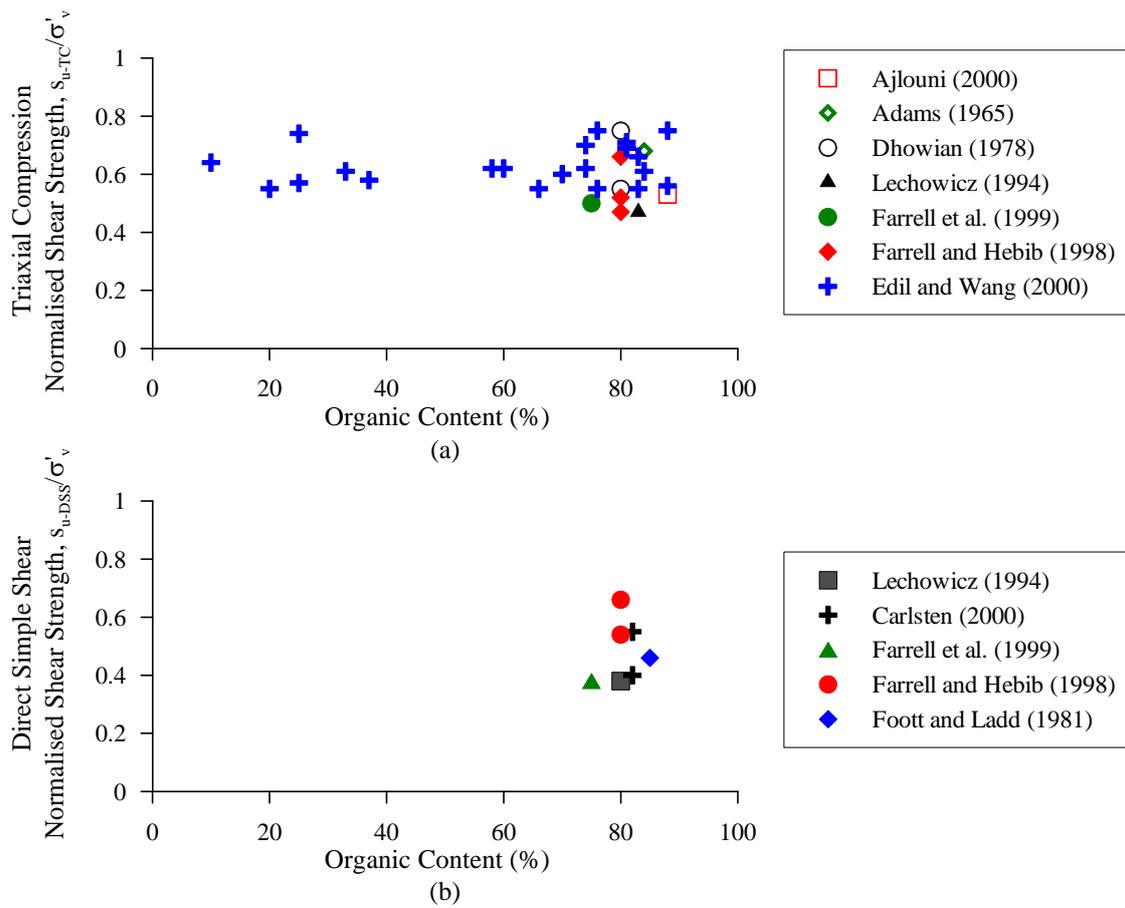


Figure 2. Summary of laboratory strengths of peat (a) Triaxial compression (b) Direct simple shear

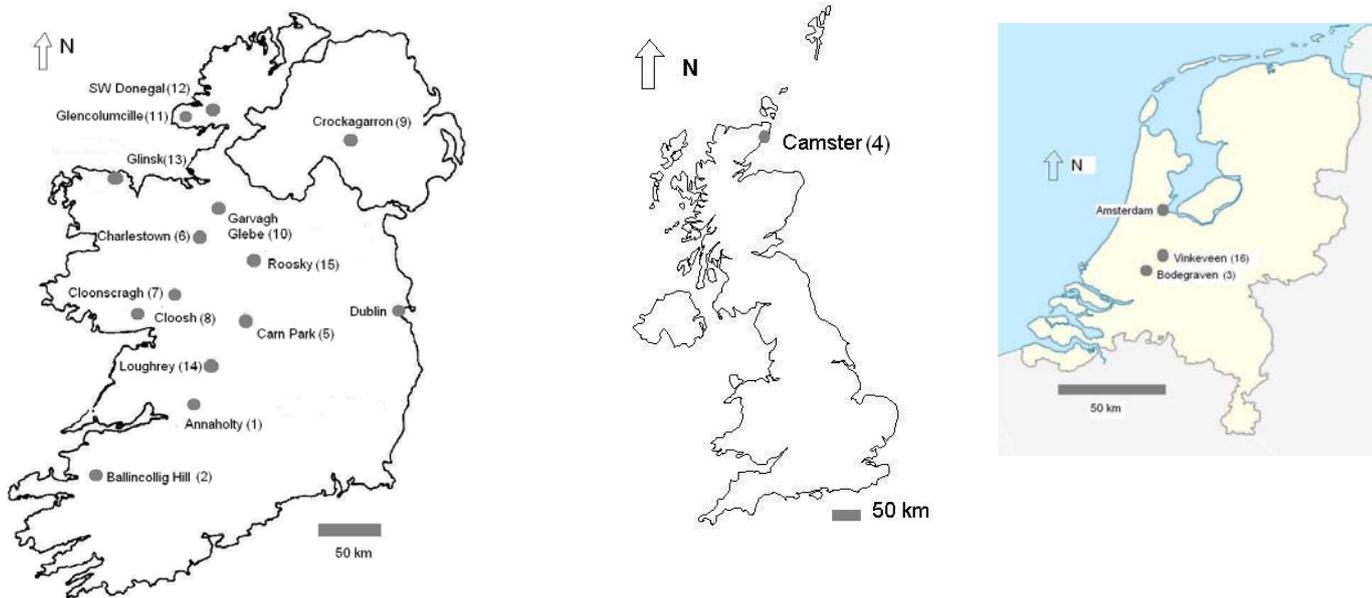


Figure 3. Site locations in Ireland, Scotland and the Netherlands

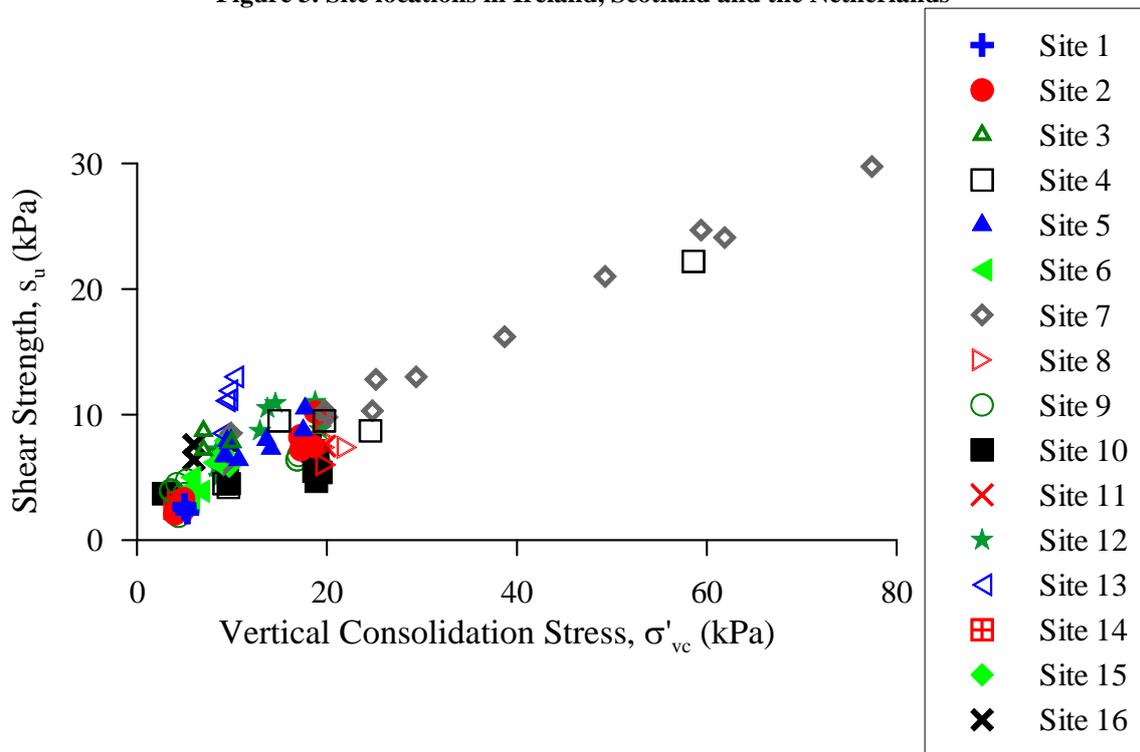


Figure 4. Results of DSS tests

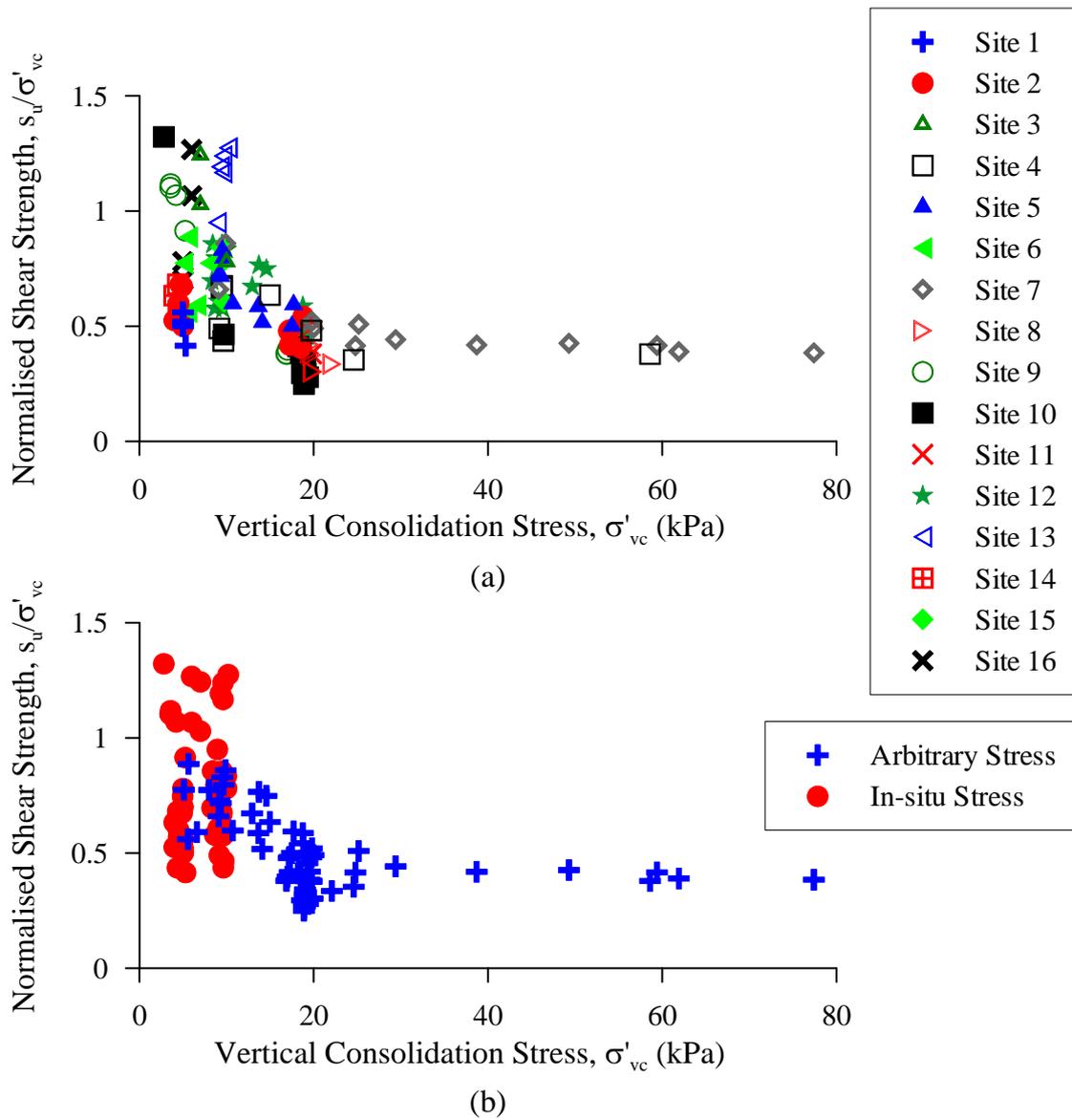


Figure 5. Normalised Shear Strengths Organised by (a) Site (b) Stress Level

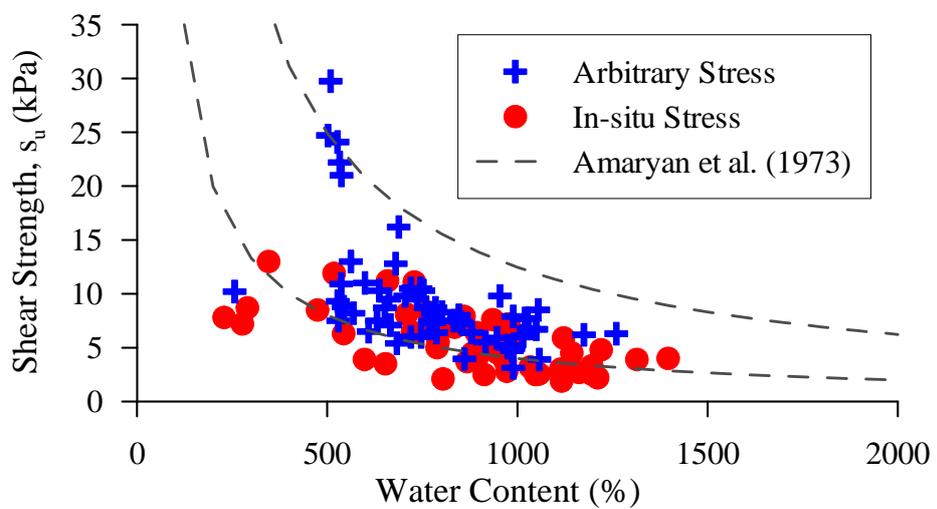


Figure 6. Variation of Shear Strength with Water Content

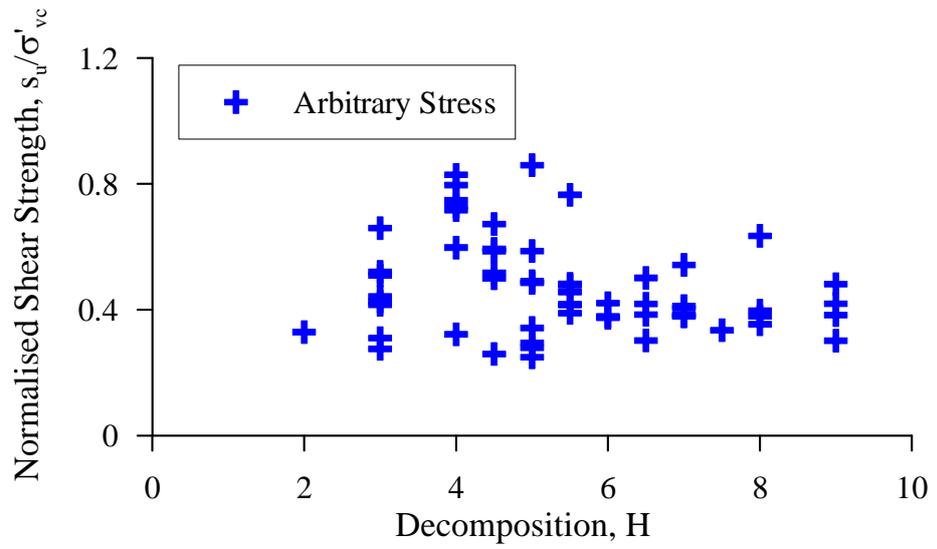


Figure 7. Normalised shear strengths versus decomposition

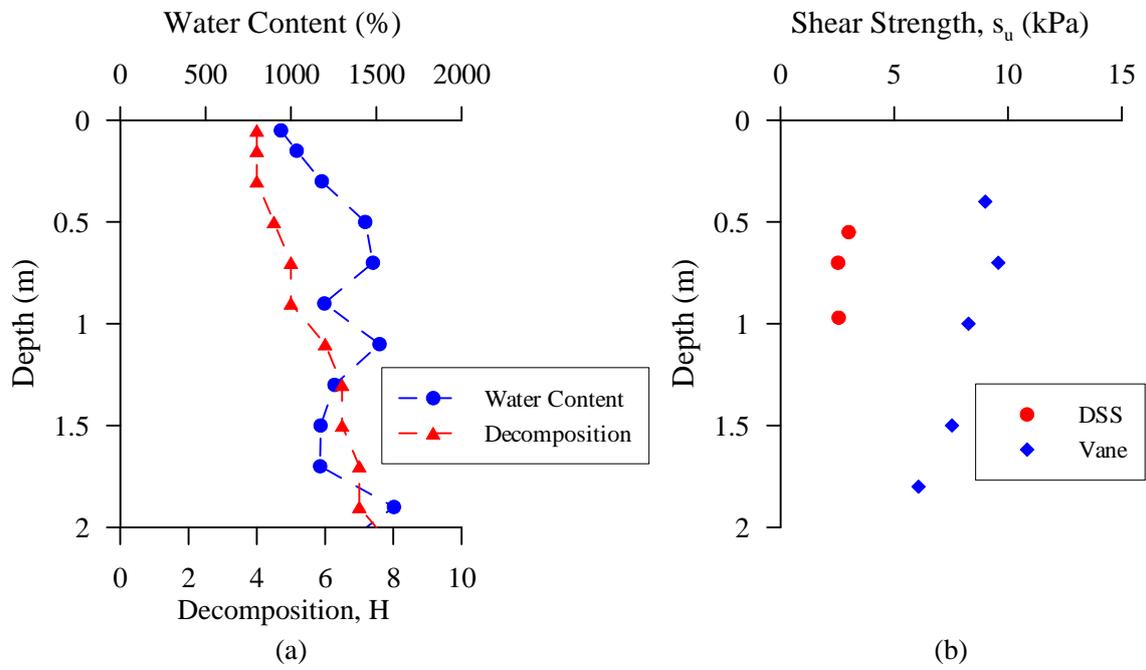


Figure 8. Loughrea Site: Comparison of Vane and DSS Strengths

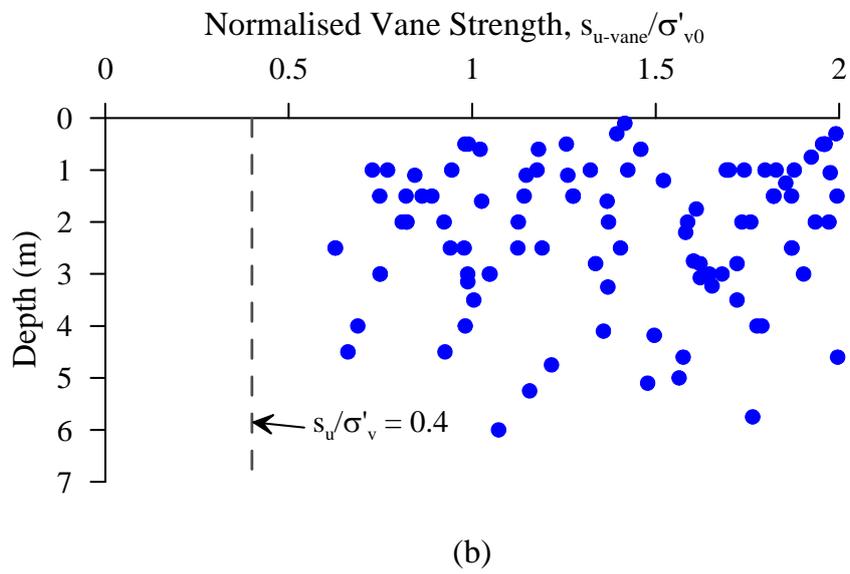
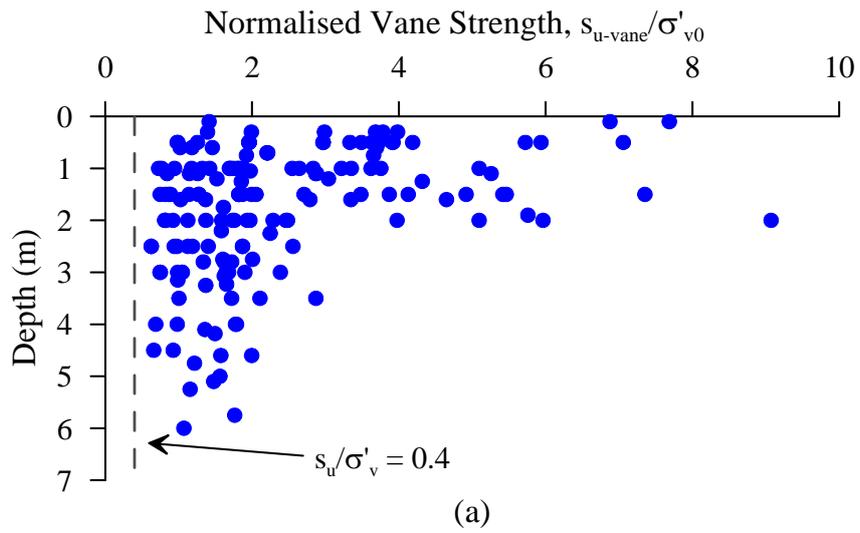


Figure 9. Normalised strengths from in-situ vane tests with depth

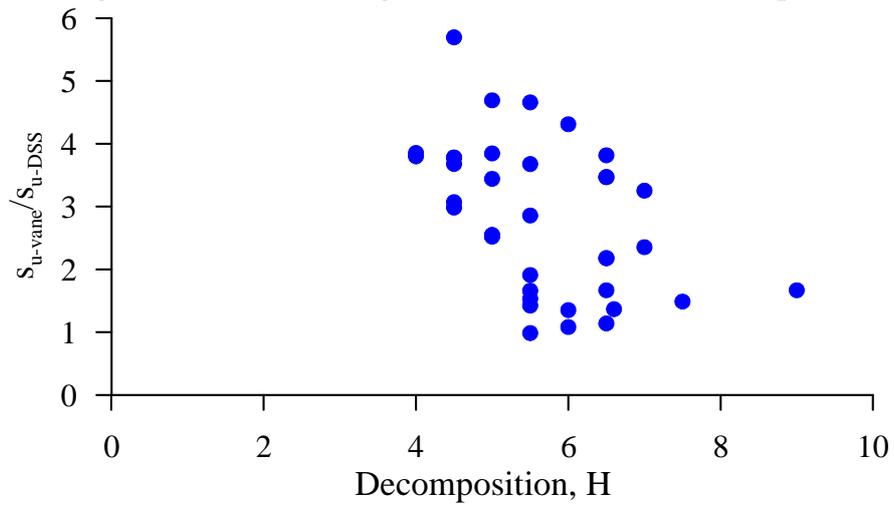


Figure 10. Ratio of in-situ vane strength compared to DSS