Evaluation of peat strength for stability assessments

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In this paper guidance is given for the assessment of peat strength for stability assessments based on laboratory undrained simple shear tests. When considering the stability of peat, these tests will yield a conservative estimate 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 simple shear tests from 16 sites in Ireland, Scotland and the Netherlands were studied. It was found that the strength of peat 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 ($\sigma_u/\sigma_{u,0}$) from simple shear 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 simple shear and field vane tests showed that 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.

1. 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 and 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, owing 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, 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 because of the wide range of causal factors that have been noted to play a role in peat slides/flows, and also 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...
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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 450 000 m³ of peat. Cuttings in peat for drainage (Tomlinson, 1981) and excavations of peat for fuel (Prager, 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 with mineral soils such as clays and sands, assessment of the geotechnical properties of peat is complicated by its high water content and compressibility, and its organic composition. The high compressibility of peat and the need to break fibres during sampling make 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 make in situ assessment of peat strength a more favourable option in practice, with the field vane test being the test most commonly used 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. Although, traditional, 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 simple shear 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 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 with 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.

2. 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 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, or a short-duration extreme rainfall event) to drained (e.g. drying and cracking of peat during summer, or creep of peat at a significant change in the slope angle). The range of permeability values reported for peat, and its potential to change significantly under modest loading (Hanrahan, 1954; Mesri and Ajlouni, 2007), add further uncertainty to the appropriate drainage conditions to consider. To the authors’ knowledge, because 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 De Lory (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

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

where \( s_u \) is the undrained shear strength of peat, \( \gamma_b \) is its bulk unit weight, \( \beta \) is the slope angle on the base of sliding, and \( z \) is the depth of the failure surface. For these assessments, the greatest uncertainty surrounds the value of the undrained shear strength to be used.

3. Shear strength of peat

3.1 In situ testing
The field vane test (FVT) is the most frequently used device in the UK and Ireland to obtain ‘undrained’ strength parameters (\( s_{uv} \)) for peat deposits. This is despite known problems with the test in peat, which lead 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, owing to the partial drainage effects. Hellenelund (1967) and Landva (1980) also reported that a cylindrical shear surface occurred at a diameter 7–10 mm outside the edge of the blade, and that the vane shear face was shorter, owing to the compression/void mechanism described above.
Therefore the assumed failure surface, from which \( s_u\text{FV} \) is calculated, is quite different from 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 dropped suddenly and the sound of fibres tearing was heard. It is extremely difficult to quantify the influence of the fibres on the peak shear strength, and whether their interaction with the vane results in a strength that is different from the mobilised strength during other modes of failure.

Unlike mineral soils, in peat \( s_u\text{FV} \) has been found to decrease with increasing vane diameter, possibly because of the effect of the fibres, and the scale effect of these. Landva (1980) concluded that the FVT 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 \( \mu_{\text{FV,C}} = 0.4-0.5 \), and Mesri and Ajlouni (2007) suggested a correction factor \( \mu_{\text{FV,C}} = 0.5 \) to 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.

3.2 Laboratory testing

Laboratory testing of peat specimens is carried out to a lesser degree than in situ tests, largely because of difficulties handling and preparing samples, as well as problems in 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, and 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 \( \pm 2 \text{kPa} \) and it is suggested that a differential pressure transducer be used 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 simple shear apparatus to test peat at the low effective stress levels encountered in situ. Standard simple shear equipment may have difficulty consolidating to low stresses (<5 kPa).

Published data for laboratory tests on peat indicate that peat and organic soils have large normalised undrained strength ratios \( (s_u/\alpha'_i) \), 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, \( s_u/\alpha'_i \) values range from 0.47 to 0.75 for peat (OC > 80%). This is compared with the typical range of 0.3–0.35 for a normally consolidated clay or silt (Ladd, 1991). For simple shear tests, \( s_u/\alpha'_i \) 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 and 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 \( s_u/\alpha'_i \) values for peat is consistently higher than for normally consolidated clays and silts.

4. Research sites and testing

4.1 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 FVTs 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 carried out only at shallow depths, where there is minimal risk to sampling personnel from collapse of the excavation. Sampling was carried out by hand-carving blocks, and by machine- or hand-pushing various sampling tubes with either a plain or serrated edge. The SGI sampler, as described by Carlsten (1988), is an example of such a sampler with a serrated cutting edge. It is 100 mm in 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
Figure 2. Summary of laboratory strengths of peat: (a) triaxial compression; (b) simple shear

<table>
<thead>
<tr>
<th>Site number</th>
<th>Site</th>
<th>Depth range: m</th>
<th>Water content: %</th>
<th>Degree of decomposition:</th>
<th>Sample type</th>
<th>Vane testing</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Annaholty, Ireland</td>
<td>0.6–1.0</td>
<td>970–1120</td>
<td>H4</td>
<td>100 mm piston</td>
<td>No</td>
<td>Boylan (2008)</td>
</tr>
<tr>
<td>2</td>
<td>Ballincollig Hill, Ireland</td>
<td>0.8–2.5</td>
<td>530–1200</td>
<td>H5–H7</td>
<td>100 mm piston</td>
<td>No</td>
<td>Long et al. (2011)</td>
</tr>
<tr>
<td>3</td>
<td>Bodegraven, the Netherlands</td>
<td>1.1–4.2</td>
<td>220–300</td>
<td>H5–H7</td>
<td>Sherbrooke block</td>
<td>Yes</td>
<td>Boylan et al. (2011); Mathijssen et al. (2008)</td>
</tr>
<tr>
<td>4</td>
<td>Camster, Scotland</td>
<td>1.1–6.9</td>
<td>530–950</td>
<td>H5–H9</td>
<td>Rotary</td>
<td>No</td>
<td>Boylan (2008)</td>
</tr>
<tr>
<td>5</td>
<td>Carn Park, Ireland</td>
<td>0.5–2.0</td>
<td>720–1050</td>
<td>H4–H5</td>
<td>Hand-cut block</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>Charlestown, Ireland</td>
<td>0.9–1.2</td>
<td>860–1170</td>
<td>H4–H7</td>
<td>100 mm piston</td>
<td>No</td>
<td>Boylan (2008)</td>
</tr>
<tr>
<td>7</td>
<td>East Galway, Ireland</td>
<td>1.8–5.9</td>
<td>510–1060</td>
<td>H3–H7</td>
<td>100 mm piston</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>Cloosh, Ireland</td>
<td>0.1–2.5</td>
<td>570–1010</td>
<td>H6–H9</td>
<td>100 mm piston</td>
<td>Y</td>
<td>Yes</td>
</tr>
<tr>
<td>9</td>
<td>Crockagarron, Ireland</td>
<td>0.9–2.5</td>
<td>790–1260</td>
<td>H2–H8</td>
<td>Hand-cut block/SGI</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>Garvagh Glebe, Ireland</td>
<td>0.8–2.5</td>
<td>610–990</td>
<td>H5–H9</td>
<td>Hand-cut block/SGI</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>11</td>
<td>Glenholm, Ireland</td>
<td>0.5–1.5</td>
<td>770–1010</td>
<td>H4–H7</td>
<td>Hand-cut block</td>
<td>No</td>
<td>Long et al. (2011)</td>
</tr>
<tr>
<td>12</td>
<td>SW Donegal</td>
<td>0.5–2.2</td>
<td>530–980</td>
<td>H5–H8</td>
<td>100 mm piston</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>13</td>
<td>Glinsk, Ireland</td>
<td>1.3–2.3</td>
<td>350–730</td>
<td>H5–H7</td>
<td>150 mm tube</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>14</td>
<td>Loughrea, Ireland</td>
<td>0.5–1.0</td>
<td>1060–1200</td>
<td>H4–H5</td>
<td>100 mm piston</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>15</td>
<td>Roosky, Ireland</td>
<td>1.1–1.3</td>
<td>840–1120</td>
<td>H4–H5</td>
<td>Hand-cut block</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>16</td>
<td>Vinkeveen, the Netherlands</td>
<td>2.4–7</td>
<td>600–940</td>
<td>H5–H7</td>
<td>Sherbrooke block</td>
<td>Yes</td>
<td>Boylan et al. (2011); Mathijssen et al. (2008)</td>
</tr>
</tbody>
</table>

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

Table 1. Summary of research sites
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 had a 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 had a lower water content, but a similar range of degree of decomposition to the Irish sites.

4.2 Simple shear testing
Simple shear testing was carried out on 111 specimens from the research sites. These tests were carried out using two types of SS apparatus: 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 simple shear tests were conducted in both types of 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 that would occur in a truly undrained test. Dyvik et al. (1987) confirmed this assumption in a comprehensive study of constant-volume simple shear tests and truly undrained simple shear tests on normally consolidated Drammen clay.

Prior to shearing, test specimens were consolidated to either an estimate of the in situ vertical effective stress ($\sigma'_{vs}$) 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 ($\sigma'_{nc}$), and then left overnight. The following day, the specimens were sheared at a constant shear strain ($\gamma$) rate of 4% per hour. In order to maintain constant-volume conditions, the vertical displacement of the top

Figure 3. Site locations: (a) Ireland; (b) Scotland; (c) The Netherlands
cap was monitored throughout, and adjustments were 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) owing 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.

4.3 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 were used). The former is a hand-operated device, and the latter is mounted on a stand-alone unit and is driven by a computer-controlled motor. All tests were conducted at a rate of approximately 1/8/s.

5. Results

5.1 General trends

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

In Figure 5(a) the shear strengths have been normalised by the consolidation stress, resulting in the normalised shear strengths ($s_u/\sigma'_{vc}$). Values of $s_u/\sigma'_{vc}$ range from 0.25 to 1.35 across all the sites. In Figure 5(b) the tests results are grouped by those that were carried out following consolidation to the in situ effective stress ($\sigma'_u$) 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, $s_u/\sigma'_{vc}$ ranges from 0.4 to 1.35, while for the arbitrary stress group $s_u/\sigma'_{vc}$ 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 from the different stress histories of the specimens. For the tests carried out to in situ effective stresses, the specimens may be over-consolidated 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 $s_u/\sigma'_{vc}$ 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, from the stress history of the specimens.

5.2 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 fall 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 $s_{u-SS}/\sigma'_{ce}$ with the level of decomposition. Note that the results are shown only 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 $s_{u-SS}/\sigma'_{ce}$ 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 emphasises that fibres may contribute to the variability of measured peat strengths, particularly at low degrees of decomposition.

5.3 Comparison of in situ vane and laboratory strength

In situ vane tests were carried out at eight 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 simple shear tests resulted in $s_{u-SS}$ values ranging from 2.5 to 3 kPa. The ratio of vane to simple shear strength ($s_{u-vane}/s_{u-SS}$) ranges from 3 to 4 at the depths where both tests were carried out.

Figure 9(a) shows the normalised strengths for all the vane tests with depth. Figure 9(b) shows a close-up of the normalised vane strengths less than 2.0. Above 2 m, the normalised strength from all the sites ranges 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 to 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 with 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 with 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 $s_u/s_{u,sc}$ of 0.4.

To further investigate the range of strengths measured from in situ vane tests, the ratios $s_u/s_{u,SS}$ against degree of decomposition, $H$, for depths at which vane tests and simple shear tests exist at the research sites are compared in 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 $s_u/s_{u,SS}$ 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), approximately 70% of the values lie above this level, implying that a universal correction factor is insufficient for correcting vane tests in peat.

### 6. Summary

This paper describes a study of the shear strength of peat for stability assessments using the simple shear 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 with the strengths obtained in the laboratory. The main conclusions from this study are as follows.

(a) The published literature shows much scatter in the range of normalised strength ratios ($s_u/s_{u,sc}$) for peat. Trends observed in this study suggest this may be largely due to the effects of stress history.

(b) Based on the results presented in this paper, peat strength is shown to be significantly affected by stress history (either in the field or the laboratory), its water content and the degree of decomposition.

(c) For the sites examined, a lower-bound normally consolidated strength ratio for peat ($s_u/s_{u,sc}$) equal to 0.4 was obtained from simple shear testing. This coincides with the lower bound of the published data.

(d) The ratio between the shear strength measured in situ using the vane apparatus and that obtained in the laboratory simple shear tests ($s_u/s_{u,SS}$) 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.

![Normalised strengths from in situ vane tests with depth](image1)

![Ratio of in situ vane strength and simple shear strength](image2)
6.1 Advice for practising engineers
The following approach is suggested for future investigations of upland peat sites.

(a) Initially probe the site using simple methods or ideally using ground-penetrating radar to determine the underlying morphology of the peat (Boylan and Long, 2012).

(b) Hand-sample the peat at regular intervals using a gouge auger or ‘Russian’ peat sampler (Jowsey, 1966).

(c) Carry out a detailed log of the 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) and 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 disciplines (e.g. engineering geologists, geomorphologists) that may provide input into qualitative risk assessments.

(d) 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 \( (s_u/\sigma_f) \). Assumed values should be confirmed through laboratory testing.

(e) 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.

(f) Multiple tests should be carried out on peat at similar depths to assess the natural variability. It would be preferable to carry out simple shear testing, but in circumstances where this test method is not available, the use of alternative 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 need to be taken into account when assessing strength parameters.

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