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Manuscript title: Shear behaviour of peat at different stress levels

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Abstract

In this study, a series of consolidated, undrained triaxial compression tests were conducted to investigate peat shear behaviour on samples from 1.65 m depth when subjected to different stress levels from 10.4 kPa to 40.5 kPa. At the consolidation stage, the triaxial test specifically investigated the peat isotropic compressibility at low stress levels, showing an agreement with oedometer test data available in literature. The subsequent triaxial shearing stage results show most of the test data failed to reach the tension cut-off line ($q/p' = 3$), which indicated that the deviator stress may represent more of an interparticle connection than the tension of fibres and woods in peaty soils. For peat, the membrane correction effect on peat shear resistance is strain dependent; generally, small within 10% shear strain, but becomes significant above 10% shear strain. A critical state line for peat was determined based on the maximum curvature approach, where the Mohr-Coulomb model has difficulty in determining the friction angle for peat. Of the data recorded for the peat, 78% fell within the range of 30 to 60 degrees, increasing to 90.4% when ignoring points lower than 10 kPa; the previous test data for very low stress level (less than 10kPa) might not be sufficiently reliable due to limitations of conventional triaxial testing apparatus, specimen preparation and etc. In addition, organic content also plays an important role on the peat shear behaviour. In general, when the organic content exceeds 75%, the deviator stress behaves like organic soils, otherwise, the peat behaves more like a mineral soil. In peat samples with organic content higher than 75%, the direct shear box test gives higher estimates of shear strength than the triaxial shear test, but not necessarily accurate — the mechanism of direct shear acts only at the centre of a specimen, while triaxial shear can shear throughout the specimens.

Keywords: peat shear strength; membrane stiffness; stress level; maximum curvature approach; organic content

1. INTRODUCTION

Peatland is widely distributed in northern Eurasia and North America, as well as other countries worldwide, covering an area of 423 million hectares (Xu et al, 2018), which represents 2.8% of the Earth's total land surface area.

In Ireland, bogland covers an area in excess of 12,000 km² (Geography of Ireland, William, 2009), consisting of two distinct types: blanket bogs and raised bogs (Abbot, 2008). Peat mainly consists of decomposed organic matter and usually forms deposits within a few meters of the ground surface, showing distinctly different mechanical properties compared to typical mineral soils. Due to the very high water content and the complex geological conditions of peatland, over three peat landslides and other relevant peat-related geological disasters occurred per month worldwide from 1979 to 1985 (Alexander, 1985). In addition, growing energy demand and rapid urbanisation necessitate an increasing number of onshore wind farms, floating roads, intercity transportation networks and other infrastructure, some of which inevitably must be built on/across peatland. As such, for future construction projects, it is essential to understand the shear behaviour of peat and associated failure mechanisms under a variety of different stress levels (Figure 1).

In general, in situ peat has very low shear strength, typically below 10 kPa. Determining the shear strength of peat is challenging due to its high water content, organic content, variable humification degree and also inevitable disturbance during sample extraction.

Previous investigations have reported that peat has a high friction angle (ϕ') while its cohesion tends to be zero, based on triaxial tests conducted in undrained conditions (Hollingshead and Raymond, 1972; Marachi et al., 1983; O'Kelly and Zhang, 2013).

Peat is also a low cohesion or even non-cohesive soil (Hanrahan, 1952, 1954a and 1954b) due to its fibre content. Although the apparent value of effective friction angle of peat from triaxial tests is as high as 40° to 68° (Farrell and Hebib, 1998; Mesri and Ajlouni, 2007; Hendry, M.T., 2012), these values do not reflect high shear strength due to the presence of fibre. Yamaguchi et al. (1985) report lower friction angles in triaxial extension tests compared to triaxial compression tests and highlighted the difference in friction angles between horizontal (35°) and vertical (52°) specimens. The friction angles from triaxial compression tests are extremely high, with typical values between 40° and 60° reported in the literature compared to values of less than 35° which are typical for clay or silt soil.

Some past triaxial tests found that peat does not show a shear failure mode but more commonly fails due to tension cut-off, a phenomenon that occurs when the pore water pressure equals the cell pressure, reducing the effective stress of peat sample to zero (Hendry, M.T., 2012). Zwanenburg (2015) summarised the deviator stress(q)–axial strain (ϵ) relationship in peat based on data from Yamaguchi et al. (1985), Den Haan and Kruse (2006) and Zwanenburg et al. (2015) and noted that shear strength develops up to the tension cut off line, in addition to the presence of the $\sigma'_3=0$ plane. Landva and LaRochelle (1983) suggested that the tension cut-off line in triaxial tests was due to the horizontal resistance induced by fibres, which are often assumed to be primarily horizontally aligned.

Table 1 shows data from previous investigations of triaxial tests on peat subject to different stress levels. Values of 0 to 10 kPa were mainly considered for peat slope stability analysis, whereas 10 to 50 kPa values were applied to specimens to examine peat response under a railway or dam.

Due to its low compressibility, the excessive deformation of peat also poses a challenge in engineering practice not only during construction but also in the long term. Mesri and Ajlouni (2007) reported that the main factors influencing peat compressibility include the fibre content, natural water content, void ratio, initial permeability, natural arrangement of soil particles, inter-particle bonding, etc. In addition, organic matter substantially affects the compressibility of peat soil based on the degree of humification. In general, there are three decomposition levels for peat soils, namely, fibric, hemic and sapric. Among these, the compressibility of fibric peat is the highest due to the presence of hollow structures absent in the other types; increasingly lower compressibility values are typical of the hemic and the sapric peat types (Huat et al., 2014).

Previous studies have mainly conducted oedometer tests to investigate the compressibility of peat. O'Kelly (2005) tested fine and coarse peat separately and found compression index (C_c) values of 5.8 for fine peat and 4.2–4.6 for coarse peat. Furthermore, O'Kelly (2006) gave a range of C_c in fine to coarse peat samples values from 0.28 to 6. Johari (2015) tested peat soils with different particle sizes from 0.3mm to 3.35mm; their results show that the value of C_c ranges from 1.7 to 2.364 and the Coefficient of Volume Compressibility (m_v , m^2/MN) ranges from 0.012 to 25.613. Gofar (2006) also conducted one-dimensional consolidation tests on peat specimens in the horizontal and vertical directions — their results showed that the value of C_c is 3.128 in the vertical and 2.879 in the horizontal direction, while the value range of m_v is 0.0014 to 0.00331. However, there is a paucity of triaxial consolidation testing data for peat compressibility to compare to the results of one-dimensional oedometer tests. The compressibility of peat in 3D space at different stress levels thus remains to be investigated; understanding this aspect of peat behaviour is crucial for a wide range of engineering applications in particular.

In this study, we conducted 14 consolidated, undrained triaxial tests following the BS1377-8 (1990) to investigate the shear behaviour of peat samples subjected to different stress levels. The experimental data are compared against previous studies' oedometer and triaxial test results. The results of this work have important implications for determining peat's compressibility and shear properties and, particularly, examining the effect of membranes on deviatoric shear stress.

2. CONSOLIDATED UNDRAINED TRIAXIAL TESTS

In this study, the peat specimens were obtained from a wind farm located in Omagh, Northern Ireland. The samples were taken from a depth of 1.65 m below the ground surface and subjected to different stress levels from 10.4 kPa to 40.5kPa. For each stress level, there were ~3–4 repeated triaxial tests of peat samples (14 in total) at the same depth to minimize experimental errors. The blocks were excavated carefully; the central part was then cut with a flat shovel to minimize sample disturbance.

In previous peat triaxial tests, a variety of specimen diameter ratios were adopted in different CU tests, for example, 1.7 by Boylan (2008), 1.3 by Garnier (2007) and 2.0 by Hendry et al. (2012). The majority of these adopted a 1.7 specimen diameter ratio (Boylan, 2008). In line with previous unconsolidated undrained (UU) peat tests (Wang, 2021), a height to diameter ratio of 1.7 was used for the triaxial specimen dimensions for the peat UU tests in this study, as suggested by Berre (1982) and Boylan (2008). Table 1 lists the physical properties of the 14 peat specimens subject to different confining stresses. On average, the water content for the tested peat is around 1,100%. At the beginning of each CU triaxial test, the specimen was fully saturated with a B-value (indicating the degree of saturation) greater than 0.97. After the saturation stage, the specimen was consolidated subject to different confining stress values

ranging from 10.4kPa to 40.5kPa. The higher the confining stress, the smaller the diameter and height of specimens after consolidation. In the final shearing stage, the specimens were slowly sheared up to 40% shear strain at a rate of 0.0118mm/min in an undrained condition.

2.1 Consolidation stage

During the consolidation stage, it usually takes 24 to 48 hours for a peat sample to complete the excess pore water pressure dissipation due to its high compressibility and low permeability.

As shown in Table 1 above, the void ratio ranges from 20.772 to 22.664, which is more than 20 times the value of typical clay. After the consolidation stage, the diameter decreased by 10.9% on average and the height decreased by 11.7%. These large decreases led to a quite significant volume change during the consolidation stage from 10% to 35%, with an average value of 27.55%. This also indicates that the highly variable moisture content of peat will strongly affect its shear behaviours, such as the friction angle and cohesion.

Based on the triaxial tests at the consolidation stage and the basic properties of specimens, Figure 2 shows the mean effective stress versus volume change during the consolidation stage; accordingly, the compression index C_c is determined to be 0.3691 and the coefficient of compressibility m_v is 0.051 to 0.2 m²/MN for peat at stress levels from 10.4 kPa to 40.5 kPa. The measured peat compressibility properties from triaxial tests in this study are similar to oedometer test results from past investigations, which reported that C_c ranges from 0.28 to 6 and m_v ranges from 0.0014 to 25.61 m²/MN for confining stresses ranging from 5 to 320 kPa (O'Kelly, 2005; Johari, 2015; Gofar, 2006), as shown in Table 2 below.

The Coefficient of Volume Compressibility curves (ε vs. vertical effective stress, p' plots) for the peat samples calculated using a triaxial tester in this study are shown in Figure 2. The m_v values for the undisturbed tests ranged from 0.051 to 0.2 m²/MN and are within the lower range of C_c values for peat in previously published literature. The compressibility curves (ε vs. \log of vertical effective stress, p' plots) for the peat samples tested using a triaxial tester in this study are also shown in Figure 2. These data are presented with a line of best-fit. The compression index, C_c , represents the slope of the ε vs. $\log p'$ plot for the incremental triaxial loading test ($C_c = \Delta\varepsilon/\Delta\log p'$); in this case, the C_c value for the undisturbed tests is 0.3691, which lies within the lower range of C_c values for peat in published literature.

Comparing the C_c and m_v values obtained in this study to those in previous publications, although both values plot within the expected range from literature presented above, they nonetheless both have much lower values than the majority of previously published results. Many of the studies described above used one-dimensional compression tests where the vertical effective stress typically increased from 10 kPa to 400 kPa, while the vertical effective stress values in this study were only in the range 10–40 kPa. This significant difference between the vertical effective stress ranges may represent a potential reason to explain the lower values of C_c and m_v recorded in this study. O'Kelly (2006) also presented an increase in the C_c value from 0.59 to 6 corresponding to a vertical effective stress increase from 12.5 kPa to 200 kPa, indicating that increasing the vertical effective stress may cause the compression index value to increase.

2.2 Deviator stress and shear strain

In the test, the deviator stress $(\sigma_1 - \sigma_3)$, measured in kPa, is derived following BS1377-8 (1990):

$$\sigma_1 - \sigma_3 = (\sigma_1 - \sigma_3)_m - \Delta(\sigma_1 - \sigma_3)_{mb} \quad (1)$$

Where $(\sigma_1 - \sigma_3)_m$ is the applied axial stress by the axial loading cell;

$(\sigma_1 - \sigma_3)_{mb}$ is the membrane stiffness correction.

2.3 The effect of membrane stiffness

Henkel and Gilbert (1952) stated that membrane stiffness, E_m , may cause potential increases in the deviator stress. Raghunandan (2014) observed that the rubber membrane used in tests has a significant influence on both measured deviatoric stress and volume change data in laboratory triaxial tests; hence, the measured test data need to be corrected by a suitable equation to minimise the membrane effect. The thickness of the membrane and the type of membrane material control the value of E_m , therefore, determining the thickness and stiffness of the membrane are essential before performing any correction procedure.

In terms of the membrane stiffness effect, an equation from the American standard ASTM D 4767-95 and Henkel (1952) is adopted to correct the deviator stress, as shown below:

$$\Delta(\sigma_1 - \sigma_3)_{mb} = \frac{4E_m t_m \gamma}{D_c} \quad (2)$$

Where D_c is the diameter of specimens after the consolidation stage, $D_c = \sqrt{4A_c\pi}$, and A_c is the post-consolidation average cross-sectional area of the sample (in mm).

t_m is the total thickness of the membrane enclosing the specimen, which is usually taken as 0.2 mm.

E_m is the Young's modulus for the membrane material; a typical value for this parameter for a latex membrane is 1,400 kPa.

The triaxial shear strain increment (γ) is given by David (1990):

$$\gamma = \frac{2(\Delta\varepsilon_a - \Delta\varepsilon_r)}{3} \quad (3)$$

Where, in the undrained test (Powrie, 1997), $\varepsilon_{vol} = \varepsilon_a + 2\varepsilon_r = 0$. Hence, $\varepsilon_r = -\frac{1}{2}\varepsilon_a$ and the shear strain is thus given by $\gamma = \varepsilon_a$.

Using Equation 2 & 3 above, the measured deviatoric was corrected for each shear strain value, and this correction may be ignored when the shear strain is less than 5%.

Figure 3 compares the original uncorrected deviator stress against the corrected values calculated from Equation 3 at different confining stress levels. The values marked with a * symbol in Figure 3 show the corrected deviator stress values, whereas the other curves without this symbol show the corresponding uncorrected data. As shown, there is minimal difference between the corrected and uncorrected deviator stresses when the shear strain is below 10%. As shear strain increases above 10%, the uncorrected data continue to increase gradually, whereas the corrected deviator stress reaches a peak value at 10% of shear strain, before levelling off or decreasing slightly. This indicates that the membrane stiffness contribution becomes significant above 10% shear strain in the triaxial compression tests.

To better explain the effect of membrane stiffness on the strength of peat, the correction in Equation 3 was also applied to the data collected from literature and laboratory tests presented in Table 3 below, which shows the reduction in stress for two points from each previously published study after correction using Equation 3. At 5% shear strain, the membrane effect ranges from 0.36 kPa to 1.43 kPa with an average decrease of 1.17 kPa. For 10% shear strain, the effect can result in a decrease of up to 2.52 kPa. Stress levels below 10 kPa showed a much higher relative reduction percentage than stress levels above 10 kPa — the lower the confining stress, the greater the apparent percentage reduction. This clearly demonstrates that the influence of membrane stiffness cannot be disregarded, especially at lower stress levels.

The membrane stiffness effect is a probable explanation as to why the deviator stress did not exhibit a peak value during the shear stage. These results support the findings of Raghunandan (2014) and indicate that there is a 10% reduction when applying Equation 3. Similarly, Table 3 also shows that the membrane stiffness effect can be identified when using Equation 3 (Yamaguchi, 1985; Garnier, 2007; Boylan, 2008; Zwanenburg, 2015).

3. STRENGTH AT DIFFERENT STRESS LEVELS

3.1 Laboratory Test results

After testing, the membrane of each specimen was opened. The shear behaviour of the peat specimens can be observed in Figure 4. Unlike the typical shear failure mode of mineral soils, i.e. shear bands or cracks across the specimen, a peat specimen usually retains its overall morphology without evidence of any major shear band failure observed during testing, as shown in Figure 4a. The specimens remained upright with no failure mode even at large shear strains, despite constantly increasing deviator stresses. Some specimens showed heavy cracks (Figure 4b), which were associated with deviator stresses gradually levelling off at high strain values (e.g. specimens 2, 10 & 11, Figure 5). The reason for this observation is likely due to high moisture content or large fibres in the peat causing inhomogeneous consolidation of the specimens.

Figure 5 shows the development of the corrected deviator stress with increasing shear strain at different confining stresses. To improve graphical clarity, the stress–strain relationship curves from the 14 triaxial tests are split up into 3 groups as shown in three sub-figures, rather than densely shown within one. In most of the triaxial tests, the deviator stress initially builds up rapidly with increasing shear strain and then gradually levels off or changes slightly above 10% shear strain. Notably, in tests 1, 5 and 14, the deviator stresses keep increasing at high shear strain values over 20%, probably due to the presence of large fibres inside these three specimens.

Peat shows significant differences from most other inorganic soils, which typically lack internal microstructure and fibre. Laboratory testing methods used to determine the strength properties of peat are generally the same as those used for mineral soil; however, the validity of determining the strength parameters, such as c' and ϕ' (cohesion and effective angle of shearing resistance), using this approach is questionable. The actual failure of peat in triaxial tests is also different to other soil types under large strains due to the high degree of deformation. Shear strain values not in excess of 20% are thus recommended to determine the failure of peat.

The triaxial tester can provide accurate control over the stress and pore water pressure, thus, other strength parameters can be determined using the following method. For each triaxial test, the maximum curvature point of the stress–strain curve is chosen as the first point at which the specimen shows a linear strain-hardening response (Silva and Lima, 2017). In general, the greater the confining stress, the larger the shear strain at which the maximum curvature point appears. For example, the maximum curvature point of Test 12 with a large confining stress value of 36.5 kPa occurs at a shear strain of 7.2%, whereas the shear strain of the maximum curvature point in Test 2 with a low confining stress value of 10.7 kPa is 3.16%. Thus, higher confining stress on a peat specimen will enhance the material's elasticity with greater yield stress and strain.

Based on previous studies (see Table 3 above), the deviator stress in most tests showed fairly slow changes after 10% of shear strain; in some cases, a peak value was reached, while in others the deviator stress continued increasing until the test ended. As noted above, in our study, the first point showing a linear strain-hardening response was taken as the maximum curvature point — the maximum curvature points from Figure 5 are plotted in terms of the mean effective stress versus deviator stress in Figure 6. Figure 6 shows the change of deviatoric stress q with mean effective stress p' for all the triaxial tests.

In the stress path plots (p' - q), the lower effective stress tests of ~10–40 kPa exhibit contractive behaviour with a gradual decrease in p' to the end of shearing. Most of the samples (10 out of 14) failed without reaching the tension cut-off line ($q/p' = 3$). The tension cut-off line in the stress path plot (p' - q) denotes the condition under which the cell pressure becomes zero due to the increase in excess pore water pressure of the sample. The stress path plots for the samples all fall below the tension cut-off line at an axial strain of 20%. The stress path lines that do not reach the tension cut-off line may indicate that the deviator stress is more strongly related to an interparticle connection in these samples rather than the tension of fibres and wood in peaty soils. The critical state (or critical void ratio) line is the locus of void ratio-effective stress conditions achieved after shearing a soil to large displacement and after all net void ratio changes and effective stress changes are complete (Sadrekarimi and Olson, 2009). The determined critical state of peat is also represented by the critical state line in the p' - q plot (Figure 6). The critical state line is the linear best-fit line obtained from the values of deviatoric stress at the maximum curvature point and the corresponding mean effective stress for each triaxial test, although the deviatoric stress–shear strain relationship does not result in failure until the end of the tests. In particular, the maximum curvature points in each test determined from Figure 5 is marked with a cross in this figure.

The friction angle and cohesion are two important parameters when determining a soil's strength. For determining these values, $M_{cu}=0.707$ and $K_{cu}=2$ kPa are the slope and y-intercept, respectively. Comparing our study's results with the data presented by Hendry (2012), the M_{cu} values of the specimens from the block cut are 1.5 times smaller than the remoulded specimens, while the values of K_{cu} from the block cut are higher than those of the remoulded specimens.

Based on the slope (M_{cu}) and Equation 4 below, the friction angle can be determined, which is equal to 18.43 degrees.

$$M_{CU} = \frac{6\sin\phi}{3-\sin\phi} \quad (4)$$

These results are comparable to data from previous studies shown in Table 4. The peat from the tests in this study has a relatively low friction angle compared with other natural peat — this difference is likely caused by a different percentage of fibres in the peat and its high compressibility.

3.2 Triaxial tests data from previous literature

Although a number of authors have also performed similar triaxial tests to investigate the shear behaviour of peat, most of them did not consider the effect of membrane stiffness on peat behaviour in triaxial tests. Figure 7 and Table 3 summarize the effective stress and deviator stress collected from previous studies, where Equation 3 was applied to the deviator stress to minimise the potential effect of membrane stiffness.

As shown in Figure 7, although a few curves show a continuous increase, the majority show a levelling off after the correction of membrane stiffness, implying that the membrane stiffness plays a significant role when analysing the deviator stress, which will affect the following calculations.

Hendry (2012) (Figure 7a) showed a linear strain-hardening response below 3% shear strain for reconstituted peat samples (fibrous peat of H2 classification) obtained from a field site in Alberta, Canada, with no evidence of approaching failure, even at higher shear strain values (20%) and higher effective stresses (80 kPa). The results of Zwanenburg (2015) (Figure 7b) evidence a similar linear strain response below 3% for peat samples collected near a dyke along Lake Markermeer in the Netherlands. With the membrane stiffness correction applied, most of the deviator stresses showed a level off after 5% of shear strain. An unusual point, highlighted by the red dashed circles in Figures 7(b), 8(a) and 8(b), was likely an underestimate — the author of the original publication did not speculate as to the cause of this unique point, however, we consider it is most likely to be due to test error. Boylan (2008) tested peat samples at low strength (effective stress around 5kPa) from different locations in Ireland and Northern Ireland. Large fluctuations in these values can be observed in Figure 7(c), with the deviator stress showing a decreasing trend above 8% shear strain to the end of tests. Garnier (2007) (Figure 7d) conducted three triaxial tests on peat taken under a railway in France. Even at higher shear strains (up to 25%), deviator stress still showed an upward growth trend.

The data from the Hendry (2012) study show a high shear strength value (35.33 kPa) corresponding to a low friction angle (12.84°), while the data from Garnier (2007) had a similar low friction angle (22.92°) albeit with a low cohesion (2.173 kPa). The other two studies (Figures 7c and 7d) present relatively high friction angles (40 to 63°) with low cohesion.

For peat, based on the figures presented above, with increasing effective stress, the effect of cohesion can be ignored as the friction angle plays a relatively more important role in the shear resistance of peaty soil. In peat, due to the high degree of decomposition and high level of organic content, cohesion is not only related to the soil particles but also fibres and wood, which is difficult to constrain. As such, it is challenging to represent shear strength by cohesion. The frictional behaviours of peaty soils are complicated and show such variability that the Mohr-Coulomb model is probably not suitable for assessment of their strength. Only considering the relationship between shear strength and effective stress would be a potentially better way to evaluate these soils.

Some previous studies (e.g. Zwanenburg, 2015) did not present the von Post classification of the samples under study, nor their corresponding depths and moisture contents; thus, with currently available information, it is challenging to interpret the common shear behaviours of peat and further investigation is required in this area.

The determined critical state of peat is also indicated by the critical state line in the p' - q stress space, as shown in Figure 8(a). The results of the various studies summarized above appear very different in terms of their stress–strain relationships and the resulting friction angle is also very different from the M_{cu} value. However, when all the data presented in Figure 7, in addition to the laboratory test data from this study, are summarized into one graph (Figure 8a), it is found that with exception of a few abnormal data fluctuations, most of the data fall within a similar range. In terms of the data points for the 10 to 80 kPa effective stress tests in p' - q stress space, nearly all of the samples failed to reaching the tension cut-off line ($q/p' = 3$). Specifically, 78% (69 of 88) of the samples fall within the range from 30 to 60 degrees. The points that lie outside this range with an overestimate of deviator stress are mainly those at lower stress levels (0–10 kPa) from Boylan (2008). Considering the observed high fluctuations in deviator stress at low peat strengths, this percentage increases to 90.1% when points lower than 10 kPa are disregarded (Figure 8(b)). In addition, the reliability of previous test data at such low stress level (0–10 kPa) seems questionable due to limitations of conventional triaxial testing apparatus, specimen preparation and etc. In Figure 8, most of the stress path lines which do not reach the tension cut-off line can also be considered proof that the deviator stress may be more representative of an interparticle connection than the tension of fibres and woods in peaty soils.

4. INFLUENCES ON PEAT SHEAR STRENGTH

Shear strength is one of the most important parameters in engineering design when working with any soil including peat because it is used to evaluate the soil's slope stability. If the shear strength is exceeded, the soil will fail or deform, potentially even leading to landslide formation.

To establish the value of this parameter, the most common laboratory test is a direct shear test or a direct simple shear test to determine the drained shear strength of fibrous peat. A triaxial test is frequently used to evaluate the shear strength of peat in the laboratory under consolidated–undrained (CU) conditions. This is because the results of triaxial testing on fibrous peats are difficult to interpret due to the fibres often acting as horizontal reinforcements (Huat et al, 2014). In addition, friction angle and cohesion also can determine from the consolidated-undrained (CU) triaxial test.

4.1 The organic content effect on shear behaviours

Table 4 presents data from previous studies on peat that used triaxial tests. The three different groups are: 1) the shear strength exhibited a peak value during the testing stage; 2) no peak value or level off reached; and 3) study with insufficient information;

Based on Table 4 below, the organic content of peat can affect the shear strength behaviour. From previous studies, where the organic content is below 75%, the deviator stress increased with peak values reached at shear strains from 5% to 25%. In these cases, the shear strength behaved more like that of a mineral soil and friction angles can be directly assessed from triaxial tests. However, in this scenario, it is hard to predict where the peak shear strain value would be reached. When the organic content exceeds 75%, the deviator stress continued increasing to large shear strain values at the end of tests. When the shear strength of the peat did not fail during tests, the Mohr-Coulomb model has difficulty in determining the friction

angle, instead, the maximum curvature approach proposed above can be used in this situation (Silva and Lima, 2017). One particular point can be determined when the curve reaches its maximum curvature; as the curves for peat usually continue to increase, it is unlikely that a point of zero gradient will be reached.

For the tests where peak values were not reached, friction angles were in the range from 12 to 33 degrees. The high friction angle of around 63 degrees from the study by Boylan (2008) is likely due to the very low effective stress. Similar results have been obtained by Coutinho and Lacerda (1989) on organic Brazilian soils, who found ϕ' values increasing up to 57° in organic soil with organic content increasing up to 60%. Mitachi and Fujiwara (1987) experimented on mixes of clay and organic matter and also found that higher organic content (up to 57% was investigated) correlated with higher ϕ' values (up to 52°).

4.2 Triaxial test versus Direct shear tests

A comparison is carried out below to compare the friction angles collected from direct shear tests, simple shear tests and triaxial tests in previous literature. Farrell and Hebib (1998) present the results of laboratory experiments investigating the shear strength of Irish peat from the Raheenmore bog by direct shear tests, ring shear tests and triaxial tests. The friction angle of shearing resistance, as measured in undrained triaxial compression tests, was about $\phi' = 55^\circ$. An effective friction angle $\phi' = 38^\circ$ was measured in both the direct shear box and the ring shear test, while the direct simple shear test showed a lower value of $\phi' = 31^\circ$. Further testing was carried out by Hebib (2001) on undisturbed peat samples from Ballydermot bog. The peat was between 94% to 98% organic, with moisture content values between 750% and 950%. The peat samples were tested in both ring shear tests and triaxial tests. Angles of shearing resistance of $\phi' = 21^\circ$ and 38° were obtained from the ring shear test. Similar behaviour to the Raheenmore peat was observed under undrained triaxial conditions, yielding friction angle results between 55° and 68° .

Cola and Cortellazzo (2005) present experimental research concerning the shear behaviour of two types of Italian peat through undrained triaxial tests. Their results showed friction angles between 49° and 51° . Zainorabidin and Mansor (2016) conducted direct simple shear tests and direct shear box tests to determine the shear strength of peat. The values of c and ϕ for the direct shear box test (around 37°) were higher than those achieved from direct simple shear (around 21°). These results show that direct simple shear testing is more suitable to determine the shear strength of peat. A series of consolidation and direct shear tests were conducted on samples of peat by Badv and Sayadian (2011), who reported friction angles from 32° to 45° with a vertical effective stress of 8.98 kPa to 26.94 kPa. Two sets of direct shear tests were carried out with 30% and 70% organic content, which showed that with a higher organic content of 70%, peat has a higher friction angle of 45° . Yamaguchi et al. (1985b) showed that the effect of fibre is negligible in peat studies. High friction angles within the range 50° to 85° have been reported based on previous studies on undrained triaxial tests of peat (Den-Haan and Feddema 2012; Farrell and Hebib 1998; Hebib 2001; Yamaguchi et al. 1985b).

Some papers quote very high friction angles from the triaxial test with no peak value reached; these tests are not suitable for comparison with friction angles determined from the direct shear test method due to the difficulty of determining the friction angle. As noted above, the organic content will also significantly affect the friction angles. As most triaxial test data do not show a peak value or level off, we instead recommended comparing the friction angles determined by the maximum curvature approach to the ones from direct shear tests. In this

regard, Table 4 determines the friction angles of some peat tests, where no peak value or level off is observed.

In general, the direct shear box test gives higher estimates of shear strength than the triaxial shear test (in Table 4), as a result of either the shearing mechanism or specimen size when comparing Tables 4 and 5. For direct shear box tests, the fibre in the middle of the sample is likely to affect the entire area of the specimen. Even though the direct shear box approach yields higher values of c and ϕ , it is not necessarily accurate — the mechanism of direct shear acts only at the centre of a specimen, while triaxial shear can shear throughout the specimens.

5. CONCLUSIONS

This study conducted a series of consolidated, undrained triaxial tests to evaluate the deviator stress values in peat under different stress levels. The main conclusions derived from the numerical results are as follows:

1. The findings from previous studies generally give a wide range of values at stress levels from 5 to 400 kPa in the oedometer tests, with values of the compression index, C_c , ranging from 0.28 to 6 and coefficient of compressibility, m_v , ranging from 0.0014 to 25.61 m²/MN. The consolidation data from triaxial tests in this study determined C_c to be 0.3691 and m_v to be 0.0072 m²/MN for peat at low stress levels from 10 kPa to 40 kPa, which is in good agreement with the range from previous studies quoted above and specifically investigated the peat compressibility at low stress levels.
2. For peat, the membrane correction effect on peat shear resistance is strain dependent. With increasing shear strain values over 10%, the difference between the uncorrected data and the corrected deviator stress can be up to 10 kPa, while the difference may be small when the shear strain is within 10%. The lower the confining stress, the higher the reduction percentage appears to be. This result clearly demonstrates the significance of the membrane stiffness effect and, thus, cannot be ignored, especially at lower stress levels.
3. Most laboratory test data (10 of 14 tests) in this study and previous test data failed to reach the tension cut-off line ($q/p' = 3$), which indicated that the deviator stress may represent more of an interparticle connection than the tension of fibres and woods in peaty soils, especially at a relatively high stress level greater than ~15 kPa. A critical state line for peat was determined based on the values of the deviatoric stress at the maximum curvature and the corresponding mean effective stress for each triaxial test.
4. Both our study and previous peat test data show that 78% of data for peat falls within the range from 30 to 60 degrees in p' - q stress space); this percentage may increase to as much as 90.1% when disregarding points measured at values lower than 10 kPa. In literature, rather limited past studies (e.g., Boylan (2008)) reported laboratory test data for peat shear behaviour at very low stress levels (0–10 kPa). Nevertheless, the reliability of previous test data at such low stress level seems questionable due to limitations of conventional triaxial testing apparatus, specimen preparation and etc. To increase test data reliability at very low stress level, future studies need to specifically investigate the peat shear behaviour using dedicate laboratory devices with sophisticated experimental skills.

5. When the organic content is below 75%, the deviator stress increases to a peak value, following the Mohr-Coulomb model. When the organic content is higher than 75%, the deviator stress continues increasing until the end of testing. The maximum curvature approach can be used in this scenario where the Mohr-Coulomb model has difficulty in determining the friction angle.
6. For peat with organic content over 75%, direct shear box tests tend to give higher estimates of shear strength than triaxial shear tests based on the shearing mechanism. However, the shear strength given by direct shear box tests is not necessarily accurate — the mechanism of direct shear acts only at the centre of a specimen, while triaxial shear can shear throughout the specimens.

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Notation

A_c	post-consolidation average cross-sectional area of the sample (in mm).
c_c	compression index
D_c	diameter of specimens after the consolidation stage
E_m	Young's modulus for the membrane material
K_{cu}	y-intercept
m_v	coefficient of compressibility
M_{cu}	the slope
t_m	total thickness of the membrane enclosing the specimen
γ	triaxial shear strain increment
$\sigma_1 - \sigma_3$	deviator stress,
$(\sigma_1 - \sigma_3)_m$	applied axial stress by the axial loading cell;
$(\sigma_1 - \sigma_3)_{mb}$	membrane stiffness correction.
ϕ'	friction angle

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Table 1. The physical properties of the triaxial test specimens

No.	Water content	Humification of Samples	e_0	$\Delta\epsilon$	Confining stress (kPa)	After consolidation	
						Diameter(mm)	Height(mm)
1	1,209%	H8	22.05	10.90%	10.4	46.33	79.57
2	1,225%	H8	20.772	16.70%	10.7	45.8	77.86
3	1,188%	H8	21.762	19.10%	12.3	45.28	76.98
4	1,154%	H8	21.96	21.70%	12.5	48.2	81.9
5	1,209%	H8	21.762	25.90%	17.8	44.35	75.39
6	1,173%	H8	22.644	22.20%	18.4	46.78	79.53
7	1,124%	H8	21.42	24.40%	21.4	44.86	72.67
8	1,258%	H8	21.636	25.80%	29	49.03	83.35
9	1,202%	H8	21.168	40.20%	31.7	41.04	69.77
10	1,176%	H8	21.114	38.20%	32.6	42.59	72.4
11	1,190%	H8	21.204	37.80%	36.5	40.76	69.29
12	1,234%	H8	21.618	35.50%	36.5	41.81	71.077
13	1,159%	H8	20.862	31.90%	37.5	45.19	70.067
14	1,194%	H8	21.384	35.40%	40.5	41.547	70.6299

Table 2. Details of Oedometer tests from previous studies

Compression index C_c	Coefficient of Volume Compressibility, m_v (m^2/MN)	Confining stress level (kPa)	Test type	Reference
5.8	N/A	12.5 to 200	Oedometer test	O'Kelly B.C (2005)
4.6				
4.2				
2.9 to 4.7	N/A	25 to 400	Oedometer test	Dhowian. A. W. and Edil. T. B. (1980)
0.28 to 6	N/A	12.5 to 200	Oedometer test	O'Kelly (2006)
1.7 to 2.36	25.61 to 0.012	5 to 320	Oedometer test	Johari (2015)
2.879 to 3.128	0.0014 to 0.0033	25 to 200	One-dimensional consolidation	Gofar (2006)
0.59 to 6	N/A	12.5 to 200	Oedometer test	Brendan (2006)

Table 3. Comparison of deviator stress between the initial uncorrected data and the data after membrane correction

		Deviator stress (kPa)						
No	Stress level (kPa)	5% of shear strain			10% of shear strain			Reference
		Initial data	Data after correction	Percentage reduction	Initial data	Data after correction	Percentage reduction	
Triaxial test data in this study								
2_10.7kPa	10.7	10.93	9.75	11%	13.32	10.98	18%	Laboratory tests in this study
4_12.5kPa	12.5	11.19	9.91	11%	13.40	10.89	19%	
13_37.5kPa	37.5	23.03	22.67	2%	27.48	24.98	9%	
14_40.5kPa	40.5	28.03	26.67	5%	38.05	35.80	6%	
Triaxial test data in literature								
CIUC-001_0.77	5	4.03	2.72	33%	5.20	2.69	48%	Boylan (2008)
CIUC-002_0.77	5	7.48	6.18	17%	9.76	7.26	26%	
CIUC001	15	14.19	12.91	9%	18.12	15.60	14%	Garnier (2007)
CIUC002	30	25.52	24.09	6%	30.04	27.52	8%	
Canada 1	24	37.06	35.87	3%	45.29	42.99	5%	Hendry (2012)
Canada 2	49	52.98	51.83	2%	62.86	60.51	4%	
Amsterdam 1	5.52	9.85	8.72	11%	10.77	8.51	21%	Zwanenburg (2015)
Amsterdam 2	6.68	10.15	8.98	12%	11.69	9.35	20%	

Table 4 Details of triaxial tests from previous studies

friction angle, ϕ' (°)	Organic content (%)	Reached peak value?	Shear strain of maximum curvature or peak value determined	Method to determine the friction angle	Reference
<u>Peat with over 75% organic content</u>					
25.69	90–96	No	8–22%	Maximum curvature method	Ajlouni (2000)
22.92	76	No	8%	Maximum curvature method	Garnier (2007)
62.99 ^{Note 1}	96	No	8%	Maximum curvature method	Boylan (2008)
12.84	82	No	5-10%	Maximum curvature method	M.T. Hendry (2010)
40.61 ^{Note 2}	75–92	No	5%-10%	Maximum curvature method	Zwanenburg (2015)
33.3	92-96	No	12%-15%	Maximum curvature method	Akeem Gbenga Amuda, Alsidqi Hasan (2019)
<u>Peat with below 75% organic content</u>					
51–55	71–73	Yes	8%	Level off	Yamaguchi et al. (1985): Undrained shear characteristics of normally consolidated peat under triaxial compression and extension conditions
35-60	60	Yes	5%	Peak value achieved	E.J. den Hann (1997): An overview of the mechanical behaviour of Peats and organic soils And some appropriate construction techniques
49–51	68–75	Yes	13%	Level off	Colleselli, Cola and Cortellazzo (2005): The Shear Strength Behaviour of Two Peaty Soils

47.3	32.4 ^{Note3}	Yes	20%	Level off	Z.X. Yang, C.F.Zhao (2016): Modelling the engineering behaviour of fibrous peat formed due to rapid anthropogenic terrestrialization in Hangzhou, China
43	43	Yes	25%	At 25% of shear strain	Stefano Muraro and Cristina Jommi (2019): Experimental determination of the shear strength of peat from standard undrained triaxial tests: correcting for the effects of end restraint
<u>Peat triaxial tests with insufficient experimental data</u>					
36.6-43.5	N/A	N/A	N/A	N/A	Hanrahan et al. (1967): Shear strength of peat. In: Proceedings of Geotechnical Conference Oslo
40-50	N/A	N/A	N/A	N/A	Landva and LaRochelle (1983): Compressibility and Shear Characteristics of Radforth Peats
55	80	N/A	N/A	N/A	Farrell and Hebib (1998): The determination of the geotechnical parameters of organic soils
42-66	83-95	N/A	N/A	N/A	Edil and Wang (2000): Shear strength and Ko of peats and organic soils

Note 1: The extremely high friction angle from Boylan (2008) is probably due to the very low effective stress (4–10 kPa).

Note 2: The higher friction angle is probably due to relatively few of the q - ε peaks developing before the end of tests.

Note 3: Organic content was calculated from fibre content=35%, $OC=100-C(100-N)$ where $C=1.04$ (Skempton and Petley, 1970).

Table 5 Details of direct shear tests / direct simple shear tests from previous studies

friction angle, ϕ' (°)	Organic content (%)	Reached peak value?	Shear strain of maximum curvature or peak value determined	Method to determine the friction angle	Reference
<u>Peat with over 75% organic content</u>					
30.4	92.5	Level off	22%	Mohr-Coulomb	Den Haan, E.J. and Grognet, M (2014)
17.8-39.8	82-89	Peak value reached	20%	Mohr-Coulomb	Saberian et al. (2017)
46.2 44.9	87.9 ^{Note4} 82.4 ^{Note4}	Critical state Peak value reached	N/A	Mohr-Coulomb	Lengkeek et al. (2014)
<u>Peat with below 75% organic content</u>					
$\gamma=10\%$, $\phi'=20$ $\gamma=40\%$, $\phi'=20-30$	73	Level off	15%	Mohr-Coulomb	Grognet (2011)
30	42–60	Level off	15%	Mohr-Coulomb	Grytan Sarkar, Abouzar Sadrekarimi (2020)
<u>Peat Direct shear tests / Direct simple shear tests with insufficient experimental data</u>					
31	N/A	N/A	N/A	N/A	Farrell ER and Hebib S (1998)
34	N/A	N/A	N/A	N/A	Farrell ER, Jonker SK, Knibbeler AGM and Brinkgreve RBJ (1999)
3-20	79-98	N/A	N/A	N/A	Bujang, B (2004)
33	N/A	N/A	N/A	N/A	McInerney GP, O'Kelly BC and Johnston PM (2006)
33.5 44	30 70	N/A	N/A	N/A	K. Badv & T. Sayadian (2011)

38	94–99	N/A	N/A	N/A	Hebib (2011)
22 37	>75	N/A	N/A	N/A	Adnan. Zainorabidin and S. H. Mansor (2016)

Note 4: Organic content was calculated from fibre content=35%, $OC=100-C(100-N)$ where $C=1.04$ (Skempton and Petley, 1970)

Figure captions

Figure 1. Effective stress levels for different ground construction projects

Figure 2. Compression Index (C_c) and Coefficient of Volume Compressibility (mv)

Figure 3. The comparison between original uncorrected deviator stress and corrected ones by Equation 3

Figure 4. Photos of specimens after tests showing the different shear failure modes. (a) Specimen with increasing deviator stress to the end of the test, (b) Specimen with deviator stress exhibiting a peak value at 40% shear strain

Figure 5. The deviator stress values, as corrected by Equation 3. (a) Group 1, (b) Group 2

Figure 6. The deviator stress q versus mean effective stress p'

Figure 7. The corrected deviator stress q versus mean effective stress p' . (a) Data collected from Hendry (2012), (b) Data collected from Zwanenburg (2015), (c) Data collected from Boylan (2008), (d) Data collected from Garnier (2007)

Figure 8. Summary of test data from previous studies. (a) Summary of test data from previous studies with a low stress level, (b) Summary of test data from previous studies without a low stress level

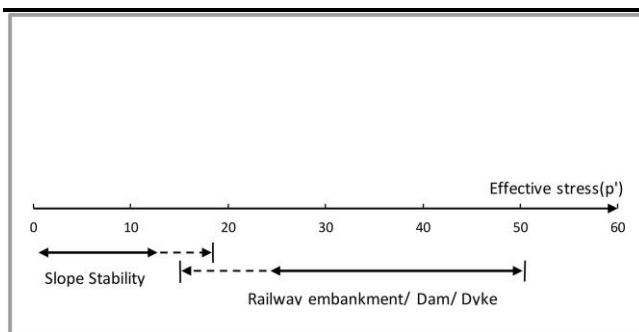


Figure 1

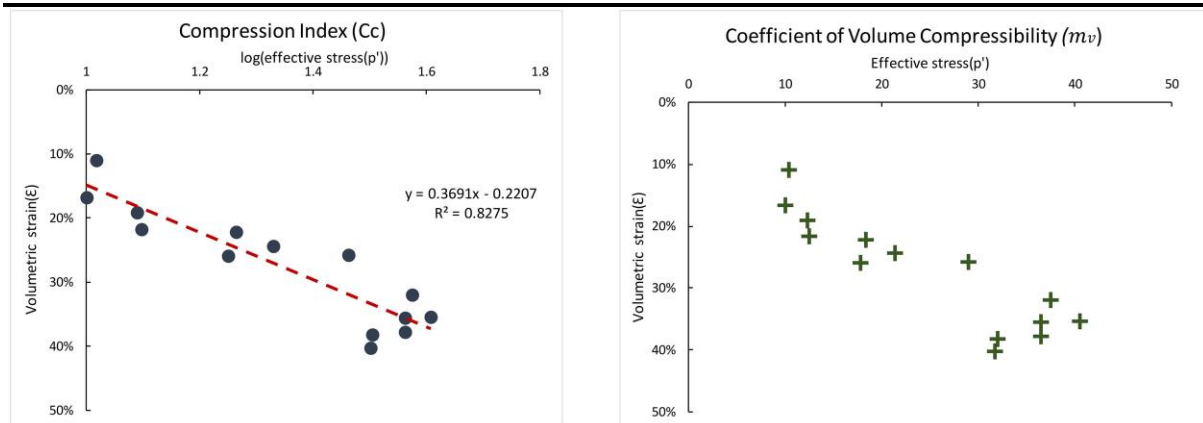


Figure 2.

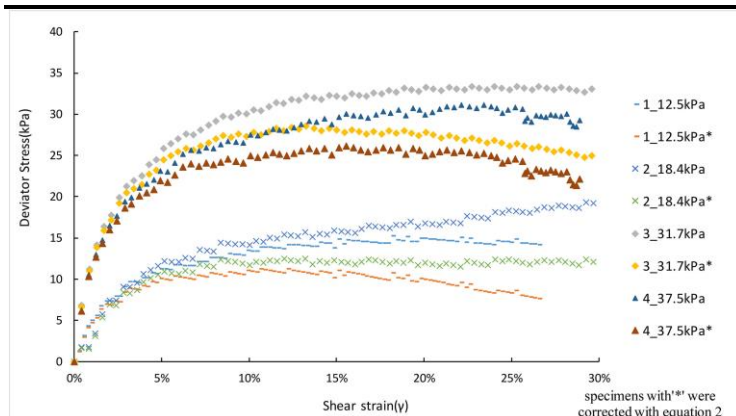


Figure 3.

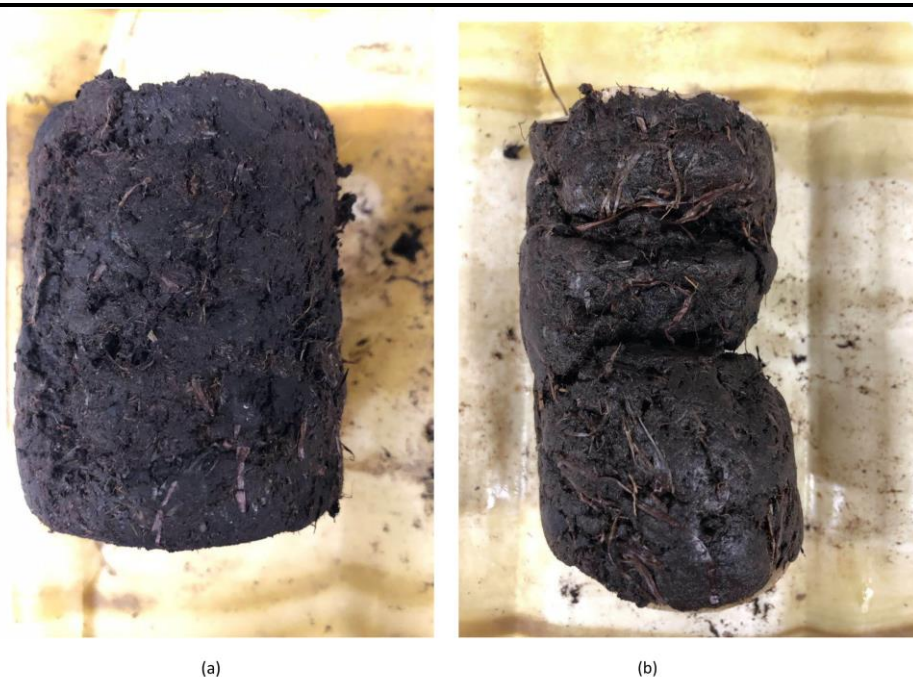


Figure 4.

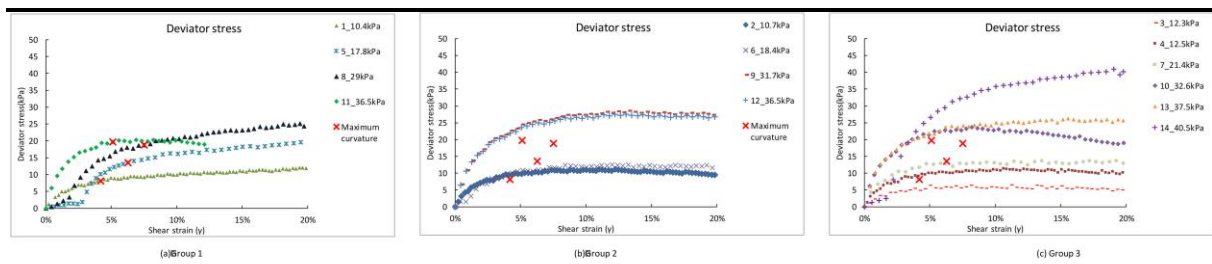


Figure 5

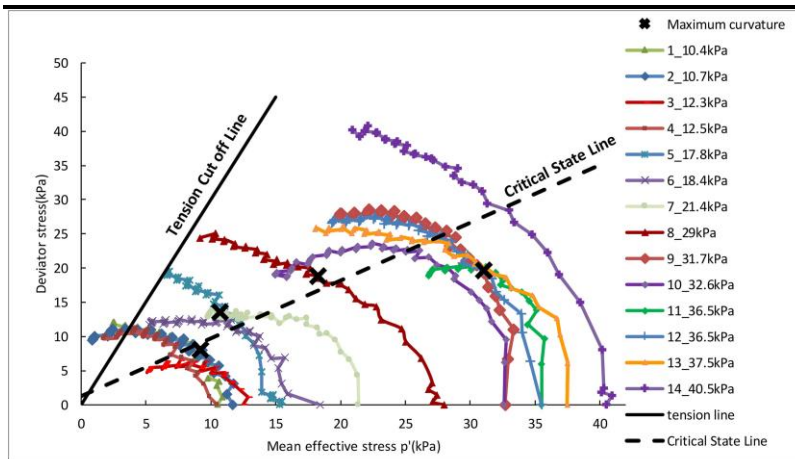


Figure 6

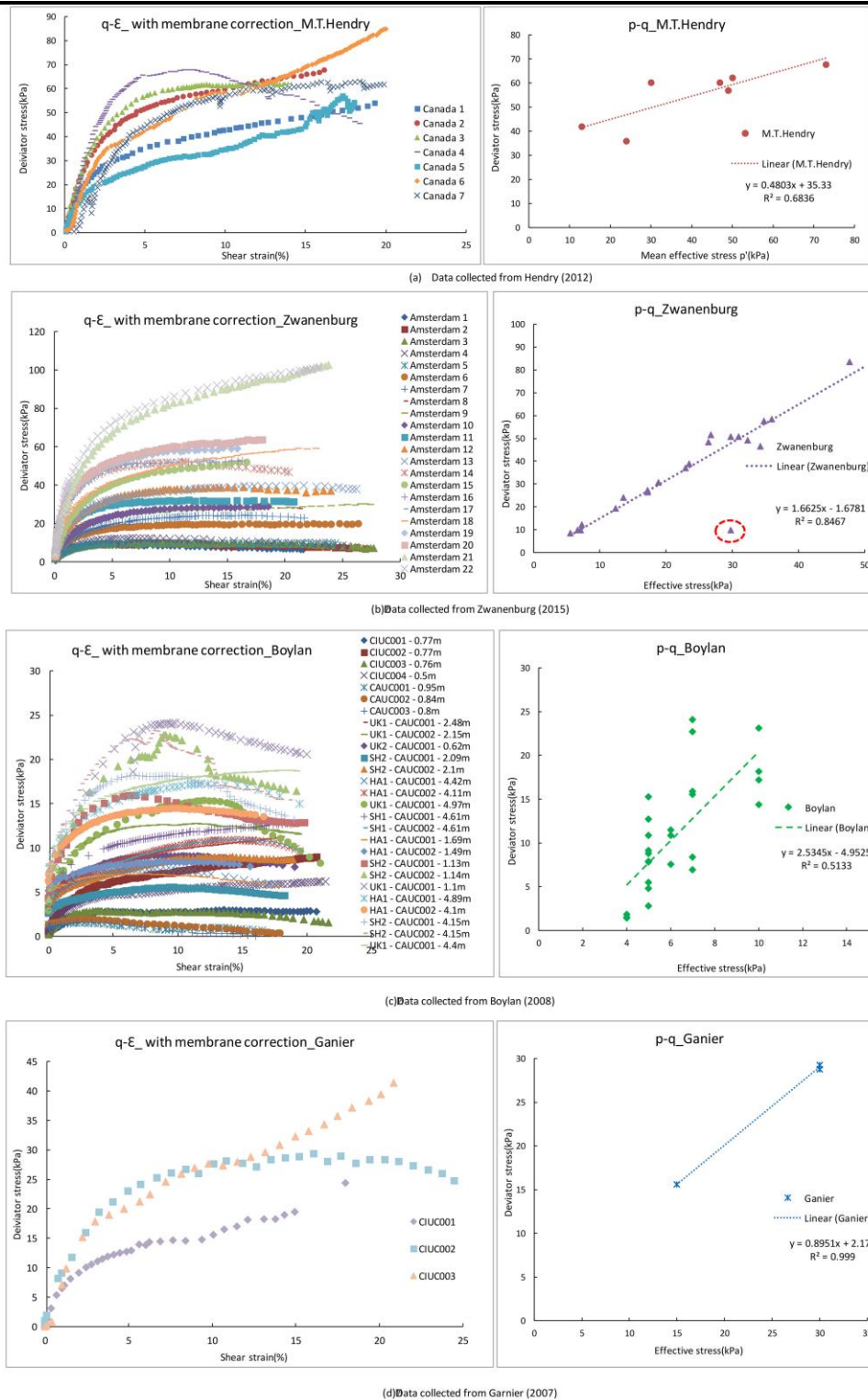


Figure 7

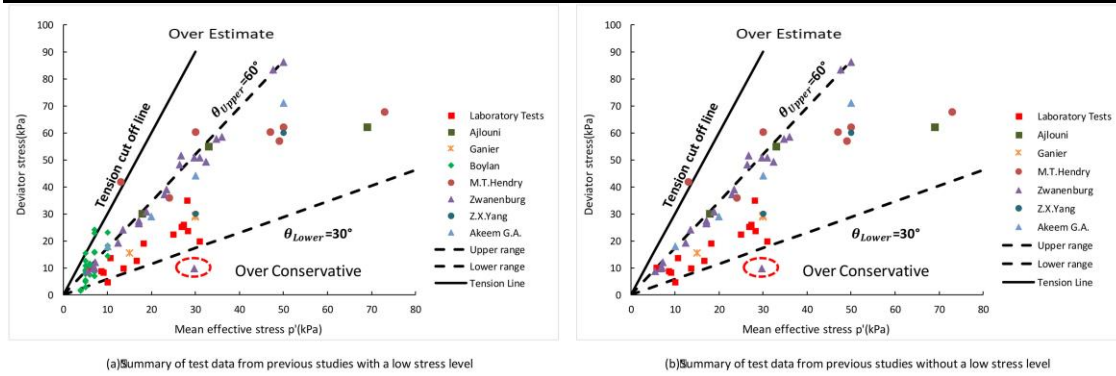


Figure 8