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Standard penetration tests in clays derived from weathered Jurassic mudstones in central England

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Abstract: Standard Penetration Tests (SPTs) are widely used in the UK for ground profiling and empirical correlation with geotechnical properties and parameters. In particular, Stroud, in 1974, related SPT N-values to undrained shear strength through an average coefficient at individual locations. Coefficients have been published for clay-rich tills and mudstone formations. However, few studies have utilized statistically useful datasets (>30 samples) or quantified the variability of the observations relative to the average coefficient.

This paper investigates these issues with reference to large datasets that were obtained from outcrops of weathered Jurassic mudstones in central England as part of a commercial ground investigation for the High Speed Two (HS2) railway. Data pairs from triaxial tests and SPTs located in close proximity (±1 m vertically, in the same borehole) were used to compare undrained shear strength and SPT N_{60}-values, and explore the variability of the observations relative to the average coefficient.

The results show that the average coefficients derived for each geological formation were close to published relationships. However, statistical analyses showed dispersion about the mean. Locally low values in the 5% fractile were between 15 and 50% of the mean value. Therefore, average coefficients are informative, but they should be used with caution.

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Standard Penetration Tests (SPTs) are widely used in the UK for ground profiling, *in situ* testing and for empirical correlations with geotechnical properties and parameters (Clayton 1995). They complement more rigorous sampling and laboratory testing by providing many measurements, and therefore a large sample size, at minimal cost (Reid and Taylor 2010). The SPT measures the number of hammer blows (the blowcount or N-value) required to drive a split barrel sampler through a seating drive of 150 mm and a main drive of 300 mm using a 63.5 kg impact weight falling from 760 mm height (British Standards Institution 2005). The SPT procedure was not standardized at its inception (Terzaghi and Peck 1948) and it is not fully standardized internationally (Skempton 1986; Clayton 1995), but current UK practice is defined by BS EN ISO 22476-3:2005+A1:2011 (British Standards Institution 2005).

The SPT has been used to estimate a range of geotechnical properties (e.g. strength, stiffness and compressibility) for granular and fine soils, and weak and weathered rocks (Clayton 1995). The empirical nature of these relationships requires them to be calibrated for specific soil and rock types (Clayton 1995). Site specific calibration may be needed for stiff clays derived from weathered mudstones, where the influence of weathering alters the structure, fabric and geotechnical properties of the clays from those of the parent mudstone (Chandler 1972; Cripps and Taylor 1981; Briggs *et al.* 2022).

In the UK, a number of correlations have been developed using an average coefficient to relate SPT N-values with the undrained shear strength of clay-like materials in fissured, clay-rich tills and in mudstone formations (Table 1). These are generally based on the Stroud (1974) relationship:

$$S_{u,UU} = f_1 \times N \qquad (1)$$

where $S_{u,UU}$ is the undrained shear strength (kPa) as measured in unconsolidated undrained (UU) triaxial compression tests, f_1 (kPa) is a coefficient that is independent of depth and discontinuity spacing and N is the SPT N-value. Stroud (1974) and Stroud and Butler (1975) showed that the numerical value of the f_1 coefficient varied with the plasticity index of the clays at the sites they examined, but this has not been shown for other soil types (Sowers 1954; Sivrikaya and Toğrol 2006; Reid and Taylor 2010). In many cases the f_1 coefficient was determined across individual sites or for multiple sites in a single geological formation as an averaged value, assuming that both the shear strength and SPT N-values increased linearly with depth at the same gradient (Stroud 1974, 1989; Stroud and Butler 1975; Sivrikaya and Toğrol 2006; Reid and Taylor 2010). In other cases, the f_1 coefficient was determined from the one-to-one comparison of individual pairs of triaxial test and SPT data located in close proximity, and then averaged to determine a single value for an individual site or geological formation (White *et al.* 2019; Crispin *et al.* 2024). White *et al.* (2019) noted that SPT samplers have changed over time and will affect the measured f_1 coefficient.

These previous studies have shown that SPT N-values can be used to estimate the undrained shear strength of clays and mudstones, but the relationship is relatively weak and correlations should be used with great care (British Standards Institution 2020). However, SPTs can be used to generate large amounts of qualitative data relatively quickly and cheaply. In addition, they are less sensitive to localized features in the ground (e.g. individual fissures) that may reduce the strength of triaxial samples. Therefore, they continue to be routinely undertaken during ground investigations to complement laboratory testing (Griffiths 2019; Reading and Lawrence West 2020). Statistical value can be obtained from

Table 1. Standard penetration test (SPT) and undrained shear strength ($S_{u,UU}$) correlations in stiff clays and weak mudstones derived from clay-rich units in the UK

Geological unit*	Model	Model coefficient, f_1 or A_1 (kN m^{-2})	Reference
Till (Glacial deposit)	$S_{u,UU} = f_1 \cdot N$	4.5–6.0, decreasing with PI	Stroud and Butler (1975) †
Till (Glacial deposit)	$S_{u,UU} = A_1 \cdot N_{60}$	4.0	Reid and Taylor (2010)
	$S_{u,UU} = f_1 \cdot N$	>6.0, for PI < 20%	Stroud (1974) †
London Clay Formation (Thames Group)	Where f_1 varies by PI	4.0–5.0, for 35% < PI < 65%	
	$S_{u,UU} = f_1 \cdot N_{60}$	5.5–6.0 for 41% < PI < 51%	White *et al.* (2019)
London Clay Formation (Thames Group)	Where f_1 varies by PI		
	$S_{u,UU} = f_1 \cdot N$	3.2–4.4, decreasing with PI	Stroud (1974) †
Woolwich & Reading Formations (Lambeth Group),	Where f_1 varies by PI		
Gault Formation (Selborne Group)	$S_{u,UU} = f_1 \cdot N$	4.4	Nash *et al.* (1996) †
	$S_{u,UU} = f_1 \cdot N$	3.3–5.6, decreasing with PI	Stroud (1974) †
Oxford Clay Formation (Ancholme Group)	Where f_1 varies by PI		
Whitby Mudstone Formation (Lias Group)	$S_{u,UU} = f_1 \cdot N$	4.0 (one result)	Stroud (1974) †
	$S_{u,UU} = f_1 \cdot N_{60}$	5.0	Stroud (1989) †
Mercia Mudstone Group*	For insensitive weak rocks		

The f_1 coefficient is dependent on the plasticity index (PI or I_p) for some overconsolidated clays in Stroud (1974).
*Re-named from Keuper Marl according to the British Geological Survey Lexicon, (BGS 2020).
† Tests prior to BS EN ISO 22476-3:2005+A1:2011.

SPTs because they are often numerous relative to other types of geotechnical measurement. The statistical interpretation of many observations can complement data evaluation based on engineering judgement by allowing the calculation of mean values and their variation for the population. This can help to avoid common mistakes in the application of engineering judgement as associated with overconfidence, a poor understanding of representativeness based on limited observations, and ignorance of prior probabilities or base rates (Tversky and Kahneman 1974; Baecher and Christian 2005).

This study examines SPT data obtained in clay soils derived from weathered mudstones in Jurassic-aged outcrops in central England. The work was undertaken in response to (1) the limited published data for SPT correlations in clays derived from these weathered mudstones, (2) the availability of statistically useful datasets (>30 samples) for the one-to-one comparison of SPTs and triaxial testing data, and (3) standardization of the SPT (e.g. British Standards Institution 2005) and weathering classification systems (British Standards Institution 2020) to improve the reliability of SPT and borehole logger descriptions, relative to earlier studies.

The aims were to (1) explore SPT correlations with undrained shear strength from a one-to-one comparison of SPT N_{60}-values and triaxial testing data located in close proximity, (2) quantify the expected variability of the correlations relative to the average, and (3) compare these with published correlations for similar geological materials.

Geology

The ground investigation included a total length of 47 km of outcrops of the Oxford Clay Formation (Ancholme Group), Whitby Mudstone Formation (Lias Group) and Charmouth Mudstone Formation (Lias Group) (Fig. 1). The geology comprised Jurassic mudstones that had been overconsolidated and then subjected to glacial, periglacial and contemporary weathering to different extents in the Quaternary period (Murton and Ballantyne 2017). Material specific weathering schemes for the Oxford Clay and Lias Clay are summarized in Norbury (2020). These conform with BS 5930:2015 +A1:2020 'Approach 4', for weak rocks (British Standards Institution 2020). The Norbury (2020) weathering classifications include unweathered (Class A) mudstone, partially weathered mudstone (Class Ba), partially weathered clay (Class Bb), distinctly weathered clay (Clay C), destructured clay (Class D) and reworked clay (Class E).

The first group of SPTs was located along a 12.4 km length in an outcrop of the Oxford Clay Formation (Ancholme Group) to the south of Buckingham, Buckinghamshire (Fig. 1). The Oxford Clay Formation (Ancholme Group) of the East Midlands Shelf comprises grey, clay-rich mudstones deposited in shallow marine conditions ~161–156 Myr ago. These form a consistent, highly bedded fabric with horizontal laminations and limited fissuring (Parry 1972; Russell and Parker 1979). The outcrop is generally ~65 m thick in Buckinghamshire (Sumbler 2002; Price 2018). Weathered clay was encountered to approximately 7.5 m bgl. This compares with the Oxford Clay Formation across central England, which includes weathered clay (Class Bb-E) to between 3 m bgl (Hird and Pierpoint 1997) and 7.5 m bgl (Russell and Parker 1979), with unweathered clay below.

The second and third groups of SPTs were located along a 34.4 km length in outcrops of the Whitby Mudstone Formation and Charmouth Mudstone Formation (Lias Group) located to the east

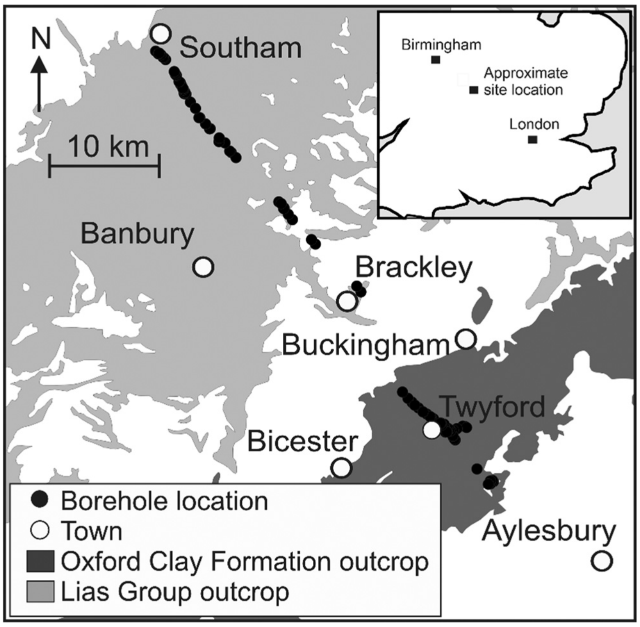

Fig. 1. The borehole locations, nearby towns and cities in relation to outcrops of Oxford Clay (Ancholme Group), Charmouth Mudstone Formation and Whitby Mudstone Formation (Lias Group). Source: contains British Geological Survey materials © UKRI 2025.

Table 2. A summary of soil laboratory testing data and SPT data for samples from 96 boreholes in the Oxford Clay Formation (OXC_w), Whitby Mudstone Formation (WHM_w) and Charmouth Mudstone Formation ($CHAM_w$)

Formation (Group)*	Number of UU triaxial tests with SPT data † ‡	Number of UU triaxial tests with soil classification and SPT data † ‡ §
Oxford Clay (Ancholme Group)	70	21
Whitby Mudstone (Lias Group)	12	1
Charmouth Mudstone (Lias Group)	53	26
TOTAL	135	48

*British Geological Survey Lexicon (BGS 2020).
† Unconsolidated undrained triaxial tests on 100 mm diameter samples to BS1377-7:1990 (British Standard Institute 2010*b*).
‡SPT to BS EN ISO 22476-3:2005+A1:2011 (British Standard Institute 2005) and assuming ±1 m offset distance.
§Tested to BS1377-2:1990 (British Standard Institute 2010*a*) and BS EN ISO 17892-1:2014+A1:2022 (British Standard Institute 2022)

and the north of Banbury, Oxfordshire (Fig. 1). The Whitby Mudstone Formation and Charmouth Mudstone Formation (Lias Group) of the East Midlands Shelf comprise grey, clay-rich mudstones and siltstones formed in shallow marine conditions ~174–199 Myr ago (Cox *et al.* 1999; Hobbs *et al.* 2012). The ground investigation data showed a gradational weathering profile of clay (Class Bb-E) and weathered mudstone (Class Ba) extending to approximately 12 m bgl, with unweathered (Class A) mudstone below (Briggs *et al.* 2022). The ground investigation data showed that the weathered clay (Class Bb-E) in the Whitby Mudstone Formation outcrop extended to approximately 8 m bgl. This compares with measurements in the Whitby Mudstone Formation elsewhere at Culworth, Northamptonshire (Chandler 1972).

The ground profiles at the borehole locations shown in Figure 1 were influenced by glacial and periglacial weathering (Moore *et al.* 2022). The Oxford Clay Formation north of Twyford was glaciated at least once in the last 450 kyr (Clark *et al.* 2004; Murton *et al.* 2015) and then experienced periglacial conditions. The Lias Group outcrop east of Banbury and towards Southam was glaciated in the last 450 kyr and experienced periglaciation conditions during the Last Glacial Maximum, approximately 26–19 kyr ago (Shotton 1953; Clark *et al.* 2004). This has altered the engineering properties of the ground. For example, Chandler (1972) showed that greater weathering correlated with increased oxidation, increased moisture content and reduced undrained shear strength in the Whitby Mudstone Formation. Coulthard and Bell (1993) showed increased fissuring, moisture content and reduced undrained shear strength in weathered samples from the Charmouth Mudstone Formation. Russell and Parker (1979) showed undrained shear strength reduction in the Oxford Clay Formation due to weakening of interparticle bonds, the solution of diagenetic minerals and the degradation of illite in weathered samples.

Method

Ground investigation data including borehole records, soil classification tests, unconsolidated undrained (UU) triaxial tests and Standard Penetration Tests (SPTs) were obtained from a ground investigation for the High Speed Two (HS2) railway between London and Birmingham. The ground investigation was undertaken by multiple contractors between 2017 and 2020. It was compiled into the digital AGS Data Format (Chandler *et al.* 2006).

Triaxial test data

Undrained shear strength ($S_{u,UU}$) values were obtained from unconsolidated, undrained (UU) triaxial tests undertaken according to BS1377-7:1990 (British Standards Institution 2010*a*, *b*), together with associated data including initial moisture content and bulk density. These data were filtered to extract results from tests on intact, 100 mm diameter, 200 mm high clay ($S_{u,UU} < 300$ kPa) samples from less than 10 m bgl. Most of the samples were obtained using cable percussion drilling and a thin wall open drive tube sampler. They were tested at a cell pressure equal to the estimated *in situ* total vertical stress. Data from other strata or test types were excluded from the analyses. The triaxial data were compared with borehole records including the strata descriptions and the visually-assessed weathering class. The weathering profile was classified during the commercial ground investigation using BS 5930:2015 +A1:2020 'Approach 4', for weak rocks (British Standards Institution 2020).

SPT data

SPTs were undertaken using either a cable percussive drill rig or crawler-mounted drill rig, in accordance with BS EN ISO 22476-3:2005+A1:2011 (British Standards Institution 2005). Data were filtered to exclude SPTs where the total number of blows needed to achieve the main drive of 300 mm (following a seating drive of 150 mm) was greater than 50. This is the limit where drilling can finish (British Standards Institution 2005) and is sometimes described as 'refusal'. The raw SPT N-values were adjusted to a reference energy ratio of 60% (N_{60}) using:

$$N_{60} = \left(\frac{E_r}{60}\right) \times N \tag{2}$$

where the N-value (N) is the number of hammer blows required to achieve a 300 mm drive length and E_r is the energy ratio of the test equipment for each test, as recorded in the borehole log.

Pairing of triaxial and SPT data

The borehole records show that the triaxial samples were all from weathered clay strata (Class Bb-E), which is consistent with the selection criteria for the data points of $S_{u,UU} < 300$ kPa. The triaxial test data were paired with SPT data located within close vertical proximity (±1 m vertically, in the same borehole). Huang *et al.* (2022) examined the spatial variability of the Oxford Clay, Whitby Mudstone and Charmouth Mudstone Formations in the vertical direction based on cone penetration test (CPT) data. The average scale of fluctuation (that is, the distance over which material properties are correlated) was calculated for each formation as 0.43, 0.33 and 0.33 m respectively. This suggests that ideally, triaxial and SPT data would have been compared for samples located within 0.33 m vertical distance. However, this was not possible owing to the length of the seating (150 mm) main (300 mm) drives of the SPT. Triaxial and SPT data were therefore considered to be in close proximity when they were located within the same borehole and separated by less than 1 m vertically, centre to centre (that is, from the centre of the triaxial sample to the centre of the main SPT drive). A total of 135 data pairs, extending up to 7.5 m bgl in weathered clay, were created in this way. There were no SPT and triaxial pairs from greater depths because either (1) SPT measurements were not undertaken in the stronger clays and mudstones at depth, or (2) the

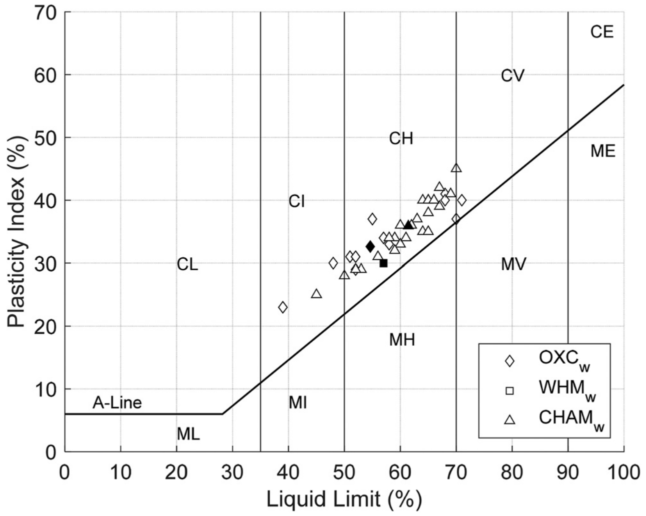

Fig. 2. A Casagrande plot showing the plasticity results for triaxial samples with associated SPT and soil classification data, categorized by formation. Values for weathered clays from the Oxford Clay Formation (OXC_w), Whitby Mudstone Formation (WHM_w) and Charmouth Mudstone Formation ($CHAM_w$) are shown. Mean values are shown as black symbols. Samples with SPT N_{60}–values < 12 were omitted.

material transitioned to mudstone ($S_{u,UU}$ > 300 kPa), which was not included in the analyses. The data were not categorized by weathering class because this created categories with a low number of data pairs that were unsuitable for regression analyses.

Table 2 shows that the SPTs were linked to 48 UU triaxial tests with soil classification data, including measurements of the liquid limit (%), plastic limit (%) and plasticity index (%). Figure 2 shows that the triaxial samples of weathered clay from the Oxford Clay (OXC_w), Whitby Mudstone (WHM_w) and Charmouth Mudstone Formations ($CHAM_w$) were mostly high plasticity, in agreement with Hird and Pierpoint (1997) and Briggs *et al.* (2022). The properties of the ground at shallow depth (the SPTs were up to ~7 m bgl) were depth-dependant, rather than elevation-dependant. This is in agreement with soil classification and strength measurements at shallow depth in the Charmouth Mudstone Formation (Briggs *et al.* 2024, 2025) and the Oxford Clay Formation (Parry 1972; Russell and Parker 1979).

Figures 3–5 show the profiles of undrained shear strength (kPa) and SPT N_{60}-values with depth for the data pairs, categorized by geological formation. The figures show an increase in both undrained shear strength (kPa) and SPT N_{60}-value with depth. However, there is significant scatter, as shown by the descriptive statistics of the mean (μ), standard deviation (σ) and coefficient of variation (*COV*) (Table 3). The *COV* is a relative measure of

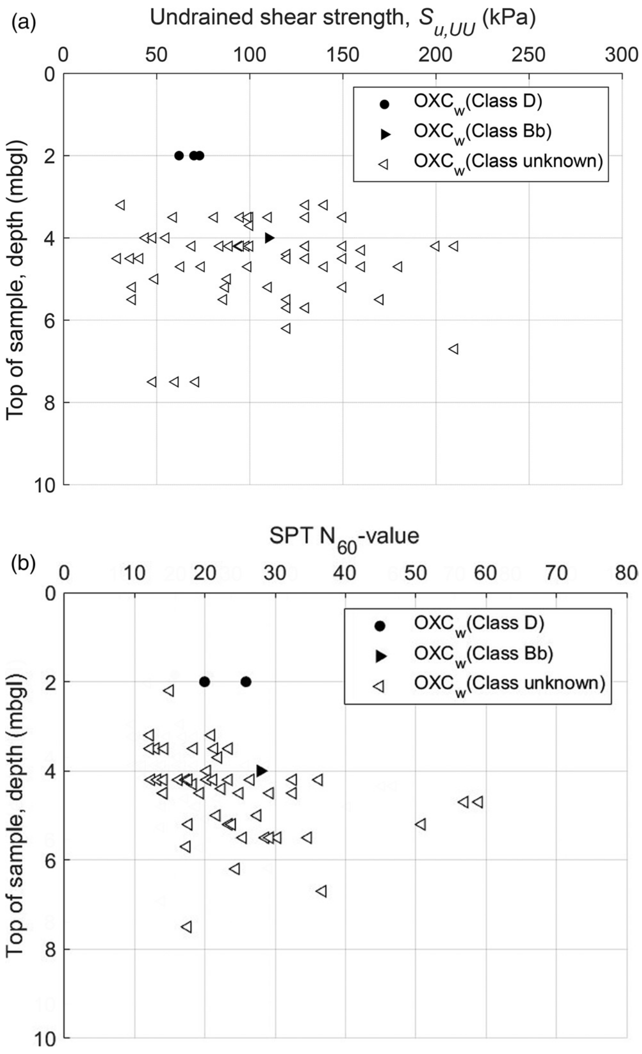

Fig. 3. Profiles for the 70 weathered Oxford Clay Formation (OXC_w) samples showing (**a**) the undrained shear strength (kPa) of the triaxial samples and (**b**) the N_{60}-values of the associated SPT tests. The weathering class is also shown.

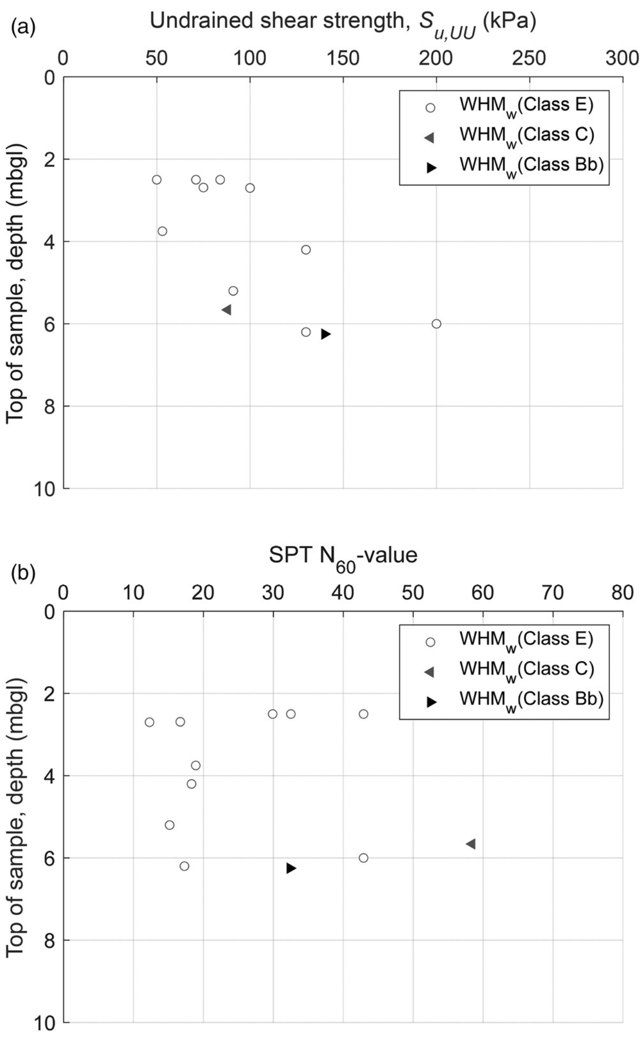

Fig. 4. Profiles for the 12 weathered Whitby Mudstone Formation (WHM_w) samples showing (**a**) the undrained shear strength (kPa) of the triaxial samples and (**b**) the N_{60}-values of the associated SPT tests. The weathering class is also shown.

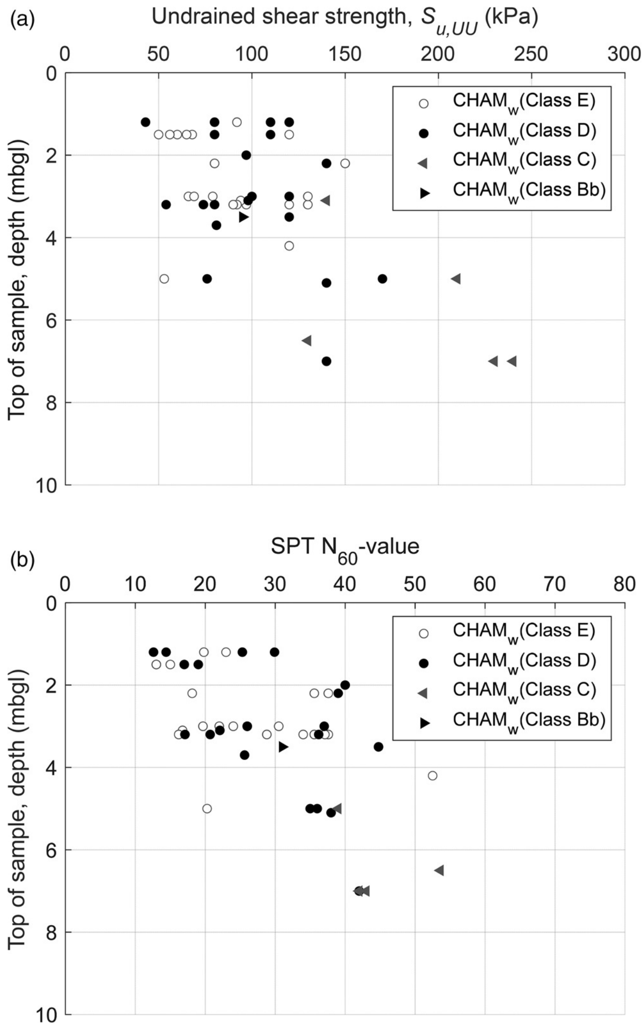

Fig. 5. Profiles for the 53 weathered Charmouth Mudstone Formation ($CHAM_w$) samples showing (**a**) the undrained shear strength (kPa) of the triaxial samples and (**b**) the N_{60}-values of the associated SPT tests. The weathering class is also shown.

dispersion that indicates the magnitude of the standard deviation in relation to the mean ($COV = \sigma/\mu$). It is used in geotechnical engineering (Phoon and Kulhawy 1999) but it is not an intrinsic statistical property (Phoon *et al.* 2022). Phoon and Kulhawy (1999) provide indicative values of the *COV* of geotechnical design parameters, including typically 30–55% for undrained shear strength measured using an *in situ* shear vane.

The scatter in the undrained shear strength (kPa) profiles of the weathered mudstones (Figs 3–5) is greater than in equivalent measurements in the London Clay Formation by Stroud (1974). This difference was also shown by Stroud (1974), who suggested that the measurements at depth in the Oxford, Kimmeridge and Lias Clays may underestimate the *in situ* strength. This may result from disturbance, fracturing and hence weakening of recovered samples, which is more likely in the relatively brittle, Jurassic-aged mudstones than in younger or more plastic clays such as those of the London Clay Formation. This is supported by the undrained shear strength (kPa) data in Figures 3–5, which include a number of strength measurements of less than 75 kPa that are present throughout the depth profile.

Interpretation

Many correlations between SPT *N*-values and undrained shear strength use a single coefficient, such as f_1, for each site or geological formation (Table 1). In this study, a single coefficient was first determined for each of the individual data pairs (f_p) shown in Table 2 using:

$$f_p = S_{u,UU}/N_{60} \tag{3}$$

where $S_{u,UU}$ is the undrained shear strength measured in an unconsolidated undrained (UU) triaxial compression test, and N_{60} is the paired SPT N_{60}-value (equation 2). There were some low SPT N_{60}-values (<12) at shallower depth (1–2 m bgl) that were associated with large $S_{u,UU}$ values and were deemed unreliable. This may result from the pairing of tests up to 1 m apart vertically, which had the greatest effect at shallow depth. Therefore, a threshold was set to remove pairs with SPT N_{60}-values < 12 from the interpretation and statistical analyses.

Coefficients were then calculated for each geological formation using two methods:

(1) Linear regression was used to calculate the f_1 coefficient with the best fit to the triaxial and SPT data pairs in each geological formation. This can be used as a predictor of undrained shear strength from SPT *N*-values, as shown for the published relationships in Table 1.
(2) Individual f_p coefficients for the triaxial and SPT data pairs were fitted to a Gaussian (normal) probability distribution function for each geological formation. This was then used to determine the average (μ) values and the distribution of the individual f_p coefficients. This can be used to assess both the most probable (average) value of the f_p coefficient in a geological formation ($f_{p,\mu}$) and the probability of higher or lower values at specific thresholds, for example at the 95% fractile ($f_{p,95}$) or 5% fractile ($f_{p,5}$).

Linear regression through the origin (an average trendline model) was used to relate the undrained shear strength (the outcome variable) to the SPT N_{60}-value (the predictor variable) using a single f_1 coefficient. This was used to find the best fit f_1 coefficient for each geological formation, for comparison with published relationships (Table 1). A linear regression through the origin was obtained by least-squares methods to obtain a single coefficient relating two variables, without the constant term required for ordinary least-squares regression. The removal of the constant term can worsen the best fit to the data but is appropriate when the constant has no physical meaning (Eisenhauer 2003), as in the interpretation of SPT data (Sivrikaya and Toğrol 2006; Reid and Taylor 2010). The *COV* for each formation was calculated to compare the dispersion of the

Table 3. Descriptive statistics for the UU triaxial test data and SPT data from the Oxford Clay Formation (OXC_w), Whitby Mudstone Formation (WHM_w) and Charmouth Mudstone Formation ($CHAM_w$)

		Undrained shear strength (kPa)			SPT N_{60}-value		
Geological Formation	Number of pairs	Mean	Standard deviation	*COV* (%)	Mean	Standard deviation	*COV* (%)
Oxford Clay	70	109	48	44	25	12	48
Whitby Mudstone	12	101	43	42	28	14	51
Charmouth Mudstone	53	111	47	42	29	11	39

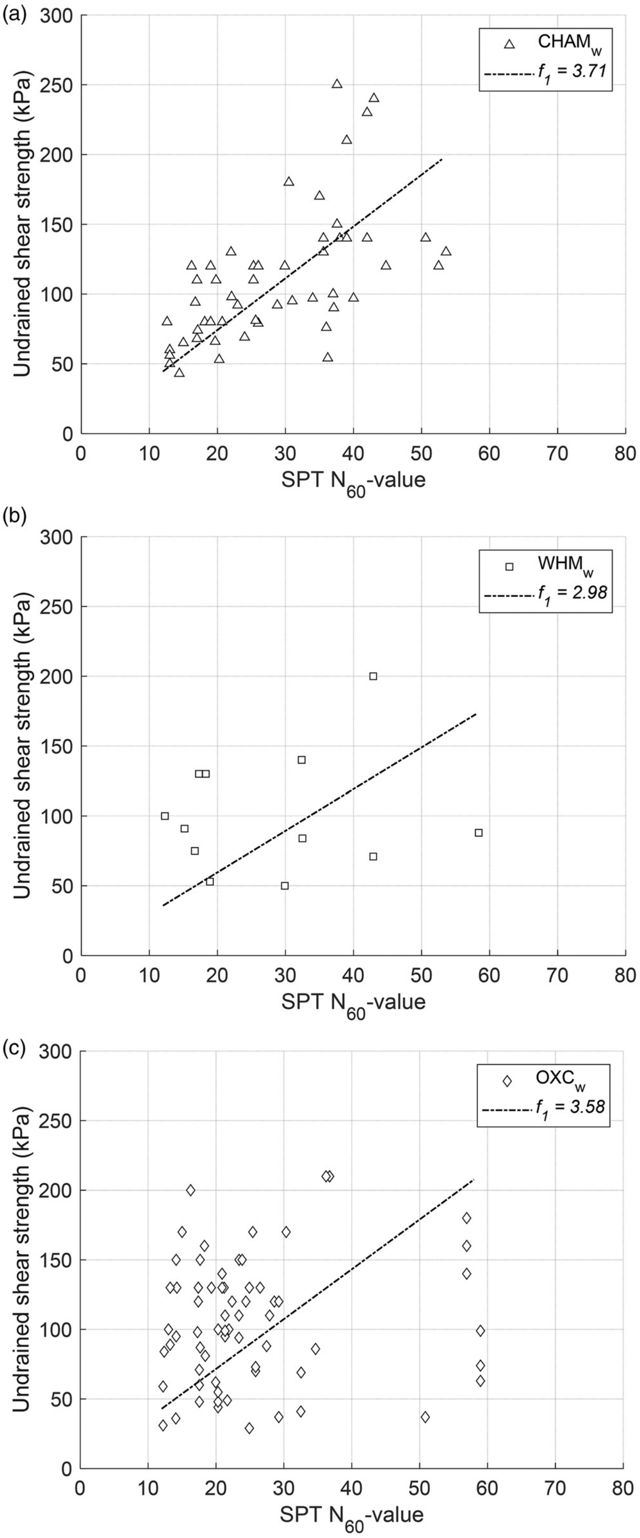

Fig. 6. SPT N_{60}-values compared to the undrained shear strength (kPa) of associated, rotary cored samples. Results and regression trend lines through the origin are shown for the (**a**) Oxford Clay Formation (OXC$_w$) ($n = 70$), (**b**) Whitby Mudstone Formation (WHM$_w$)($n = 12$) and (**c**) Charmouth Mudstone Formation (CHAM$_w$)($n = 53$). SPT N_{60}-values < 12 were omitted from the analyses. The regression coefficient (f_1) for each formation is shown.

actual undrained shear strength data from the model values. The *COV* was calculated by dividing the standard deviation of the residuals from the regression model for the undrained shear strength by the mean of the undrained shear strength. In addition, the Mean Absolute Percentage Error (MAPE) was calculated for each formation to provide a simple quantitative measure of the regression model accuracy (De Myttenaere *et al.* 2016). The MAPE is the average of the absolute percentage errors between the undrained shear strength data and that calculated using the f_1 regression coefficients.

A probability density function was used to calculate the average values for the f_p coefficients in each geological formation, and their distribution (that is, the range of f_p values and their probability of occurrence). The f_p coefficient (equation 3) was calculated for each SPT and triaxial pair ($n = 135$) and categorized by geological formation. The results were plotted as a probability histogram and fitted to a Gaussian probability density function, which has been used previously to fit both soil strength and SPT data (Baecher and Christian 2005). The probability histogram and probability density function were used to determine the average (μ) values of the f_p coefficients in each geological formation. This method was most reliable for the larger ($n > 30$) datasets of the Oxford Clay Formation ($n = 70$) and Charmouth Mudstone Formation ($n = 53$). A probability histogram and probability density function were not generated for the Whitby Mudstone Formation owing to the small size of the dataset ($n = 12$). The variance (σ^2) and standard deviation (σ) were calculated for each geological formation, to measure the variability of the f_p coefficients. From this, the *COV* was calculated, as were upper and lower values of f_p in the 95th percentile ($f_{p,95}$) and 5th percentile ($f_{p,5}$) respectively. The 5th percentile value of the f_p coefficient was calculated to show the lowest value, with a probability of being exceeded in 95% of cases.

Table 2 shows that 48 SPTs were paired with UU triaxial tests and soil classification data. These pairings were used to examine the relationship between the f_1 coefficient and the plasticity index shown in Stroud (1974). The f_p coefficient (equation 3) was calculated for each of the SPT and triaxial pairs and compared with the plasticity index of the triaxial sample. The mean values of f_p for each formation ($f_{p,\mu}$) and the plasticity index were calculated for the Oxford Clay and Charmouth Mudstone Formations. These were compared with f_1 values for the Oxford Clay and Whitby Mudstone Formations given in Stroud (1974).

Results

Figure 6 compares the SPT N_{60}-values and undrained shear strength measurements in the weathered clays, categorized by geological formation. The trend lines show that the undrained shear strength increased with the SPT N_{60}-value. The f_1 coefficients range between 2.98 (for the WHM$_w$) and 3.71 (for the CHAM$_w$). They are therefore close to the published values for the same geological formations shown in Table 1, which range from 3.3 to 5.6 in the OXC$_w$ and 4.0 in the WHM$_w$ (Stroud 1974). The *COV* values for the f_1 coefficients in Table 4 range from 36% (for the CHAM$_w$) to 55% (for the OXC$_w$). This is greater than for the SPT and triaxial data (Table 3) and towards the upper limit of *COV* for geotechnical parameters given by Phoon and Kulhawy (1999). The MAPE for the f_1 coefficients ranges from 28% (for the CHAM$_w$) to 55% (for the OXC$_w$ and WHM$_w$), showing that the regression models were more accurate for the CHAM$_w$ than for the OXC$_w$ and WHM$_w$.

Figure 7 shows the probability density histograms of the f_p coefficient for individual samples in the OXC$_w$ and CHAM$_w$, fitted to a Gaussian (normal) probability density function. From these, the mean coefficients (μ) can be used to estimate the mean coefficients for each formation ($f_{p,\mu}$). The data from the WHM$_w$ were not a good fit to the Gaussian PDF due to the small sample size ($n = 12$) and are therefore not shown. Figure 7 shows that the $f_{p,\mu}$ coefficients are greater than those derived from linear regression through the origin (Fig. 6) but lie within the range of published values shown in Table 1. Table 4 includes the *COV* of the $f_{p,\mu}$ coefficients. This shows that there was the least variation about the mean and the best fit to

Table 4. Fitting coefficients for the SPT N_{60} -value (explanatory variable) and undrained shear strength of the Oxford Clay Formation, Whitby Mudstone Formation and Charmouth Mudstone Formation samples using (1) linear regression through the origin and (2) a Gaussian probability density function (PDF) fitted to the data

Geological Formation	N	Mean coefficient (f_1 or $f_{p,\mu}$)	Standard deviation (σ)	$f_{p,5}$	$f_{p,95}$	*COV* (%)	MAPE (%)	Model range
Single coefficient								
Oxford Clay	70	3.58	N/A	N/A	N/A	55	55	$12 < N_{60} < 59$
Whitby Mudstone	12	2.98	N/A	N/A	N/A	55	51	$12 < N_{60} < 58$
Charmouth Mudstone	53	3.71	N/A	N/A	N/A	36	28	$12 < N_{60} < 54$
Gaussian PDF coefficient								
Oxford Clay	70	4.91	2.54	0.74	9.08	52	N/A	$0 < f_p < 12$
Whitby Mudstone	12	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Charmouth Mudstone	53	4.09	1.33	1.90	6.28	32	N/A	$1 < f_p < 8$

the Gaussian PDF for the $CHAM_w$ data pairs. Therefore, the $f_{p,\mu}$ coefficient for the $CHAM_w$ is the most useful of the three geological formations considered. Table 4 shows upper and lower values of f_p in the 95th percentile ($f_{p,95}$) and 5th percentile ($f_{p,5}$) respectively for each geological formation. The values for $CHAM_w$, which had the best fit to the Gaussian PDF, show that while the mean $f_{p,\mu}$ coefficient for the formation is 4.09, this ranges between a minimum ($f_{p,5}$) of 1.90 and a maximum ($f_{p,95}$) of 6.28. The range of minimum ($f_{p,5}$) and maximum ($f_{p,95}$) coefficients is greater than this for the OXC_w, but these values are less reliable than for the $CHAM_w$ owing to the poorer model fit (i.e. the Gaussian PDF).

Figure 8 shows the f_p coefficient derived from the individual SPT and triaxial pairs plotted as a function of the plasticity index of the sample, where available ($n = 48$). The results are categorized by geological formation (OXC_w, WHM_w and $CHAM_w$), with mean values for the OXC_w and $CHAM_w$ ($f_{p,\mu}$) shown in black. These are compared with the mean values from individual sites (f_1) measured by Stroud (1974) in comparable strata and the Stroud (1974) trend line relating the f_1 coefficient to plasticity index. The $f_{p,\mu}$ coefficients for the OXC_w and $CHAM_w$ lie close to those measured by Stroud (1974) in the same geological formations. However, inspection of the individual f_p results shows scatter that does not agree with the Stroud (1974) trendline. Therefore, for these data, any relationship between the $f_{p,\mu}$ coefficient and plasticity index is small relative to the variability in the individual data pairs (that is, in f_p).

Discussion

The Stroud (1974) coefficient (f_1) gives the best-fit slope from a linear regression of undrained shear strength $S_{u,UU}$ against N_{60} for each geological formation (Table 1). However, this study also computes an individual coefficient (f_p) for each data pair and the distribution of these values in each formation. A normal distribution (Gaussian) was fitted to the f_p values, allowing the derivation of mean coefficients ($f_{p,\mu}$) and percentile-based values such as the 5th and 95th percentile values, ($f_{p,5}$ and $f_{p,95}$). The f_1 coefficients reflect a regression relationship that is influenced by the spread and weighting of data across the range of N_{60}, while $f_{p,\mu}$ is the arithmetic mean average of individual data pairs. Therefore, the coefficients can have similar, but not always identical values. The percentile values derived from the histogram of f_p coefficients allow flexibility to choose appropriate coefficients for probabilistic design by re-writing equation (3):

$$S_{u,UU} = f_{p,pc} \times N_{60} \qquad (4)$$

where $S_{u,UU}$ is the undrained shear strength (kPa), N_{60} is the SPT N_{60}-value and $f_{p,pc}$ (kPa) is a coefficient for the *pc*-th percentile (*pc* is a number from 0 to 100). For example, Figure 9 shows $S_{u,UU}$ values calculated using the mean ($f_{p,\mu}$) and the percentile-based $f_{p,5}$ and $f_{p,95}$ coefficients in Table 4 for the Charmouth Mudstone Formation ($CHAM_w$). They are compared to the unconsolidated undrained (UU) triaxial compression tests (Fig. 5). As expected, the

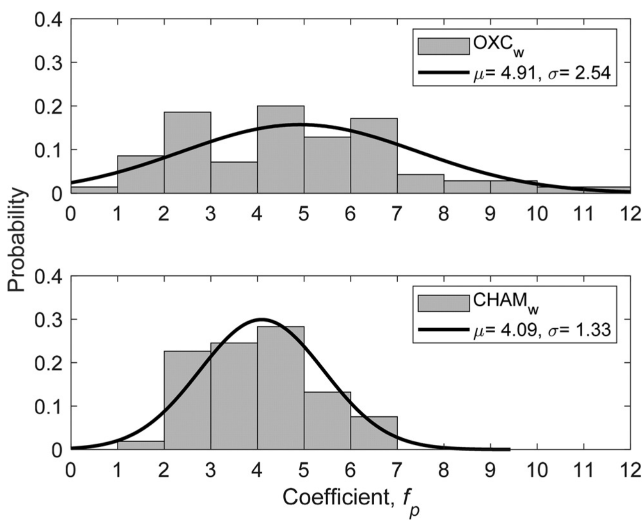

Fig. 7. The probability density and Gaussian probability density functions for the coefficient (f_p) in weathered clays of the Oxford Clay Formation (OXC_w)($n = 70$) and Charmouth Mudstone Formation ($CHAM_w$)($n = 53$). The mean (μ) and standard deviation (σ) of the Gaussian probability density functions are shown. The *COV* values are shown in Table 4.

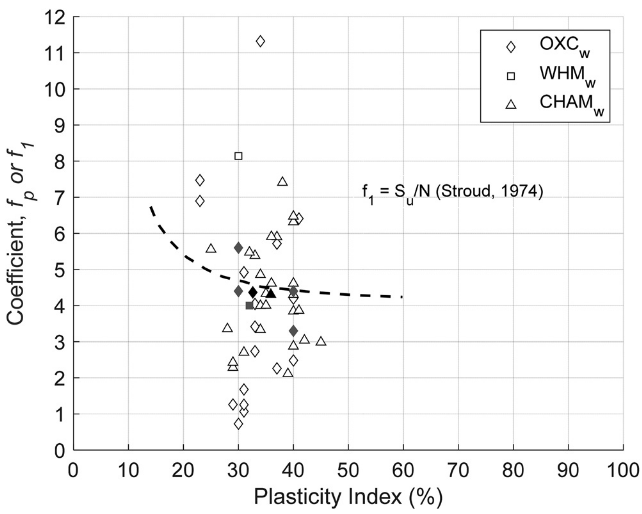

Fig. 8. Coefficients for individual SPT and triaxial pairs (f_p) compared to plasticity index for weathered clays of the Oxford Clay Formation (OXC_w) ($n = 21$), Whitby Mudstone Formation (WHM_w)($n = 1$) and Charmouth Mudstone Formation ($CHAM_w$)($n = 26$). Mean coefficients ($f_{p,\mu}$) for OXC_w and $CHAM_w$ are shown in black. Mean coefficients (f_1) measured by Stroud (1974) are shown in grey.

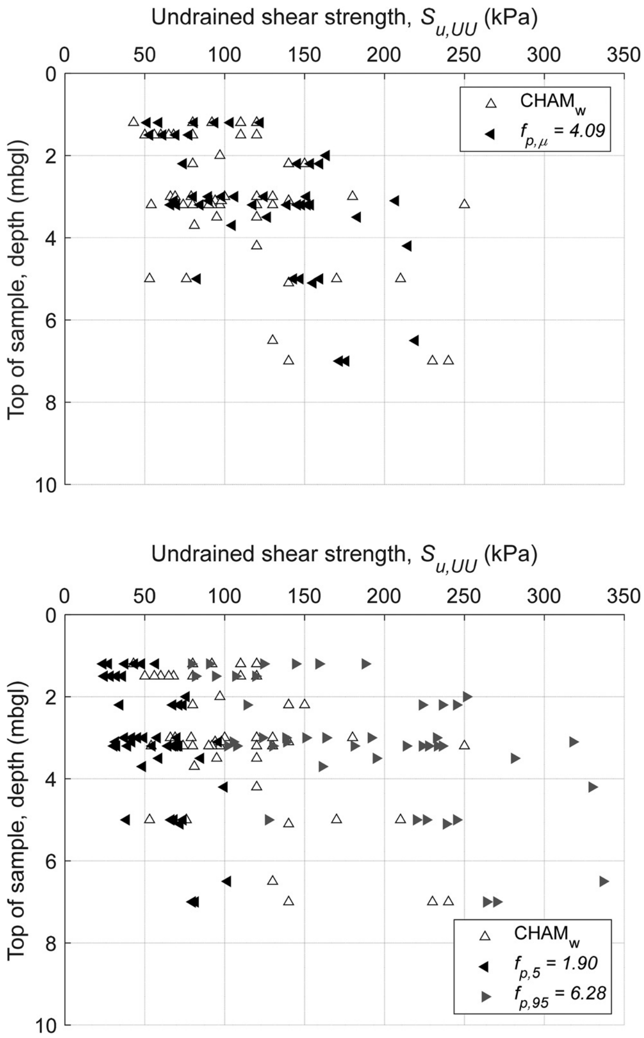

Fig. 9. Undrained shear strength from the 53 weathered Charmouth Mudstone Formation ($CHAM_w$) triaxial samples, compared with undrained shear strength derived from 53 SPT N_{60}-values, using equation (4) with (**a**) a mean average coefficient, ($f_{p,\mu}$) and (**b**) a 5th percentile ($f_{p,5}$) and 95th percentile ($f_{p,95}$) coefficient.

shear strength values calculated using $f_{p,\mu}$ fall within the range of the triaxial measurements. Undrained shear strength values calculated using $f_{p,5}$ provide more conservative values, while $f_{p,95}$ provides higher values.

Conclusions

The Stroud (1974) approach can be used to derive individual (f_p) and formation-wide (f_1) coefficients from individual pairs of SPTs and unconsolidated undrained (UU) triaxial tests in weathered clays ($S_{u,UU} < 300$ kPa). Data were examined for SPT and triaxial data pairs located in close proximity (±1 m vertical distance in the same borehole) in weathered clays from the Oxford Clay (OXC_w), Whitby Mudstone (WHM_w) and Charmouth Mudstone Formations ($CHAM_w$) in central England. The following conclusions can be drawn:

(1) Published f_1 coefficients are generally applicable to the weathered mudstones considered in this study to obtain average values of undrained shear strength from SPT blow count data. The results show that the f_1 coefficients derived using linear regression through the origin are close to published f_1 coefficients for stiff clays and weak mudstones (Table 1). However, the f_1 coefficients provide average values but do not provide information about the dispersion from the mean, which can be large.

(2) There is high variability in both the undrained shear strength (kPa) and SPT N_{60}-values in the weathered mudstones, which may result from disturbance, fracturing and therefore weakening during sampling and/or testing. The f_1 coefficients represent average values, but the results from individual pairs show that there is dispersion about the mean, with *COV* between 36 and 55% and Mean Absolute Percentage Errors (MAPE) between 28 and 55%. This supports the assertion that SPT *N*-values should be used with caution when estimating the undrained shear strength of brittle materials such as stiff clays and weak mudstones (Stroud 1974; Reid and Taylor 2010; British Standards Institution 2020).

(3) When the sample size is statistically useful ($n > 30$), a Gaussian probability density function (PDF) can be fitted to the f_p coefficients derived from individual SPT and triaxial pairs. This provides an interpretation that accounts for the range of likely f_p coefficients including the probability of lower-bound, average and upper-bound values. This allows lower-bound and upper-bound values to be considered more explicitly than when using linear regression. The results show that lower-bound f_p coefficients can be much lower than the average values. For example, results for the Charmouth Mudstone Formation ($CHAM_w$) show that the f_p coefficient reduced from a mean value of $f_{p,\mu} = 4.09$, to a lower bound value of $f_{p,5} = 1.90$. A greater reduction to approximately 15% of the mean value was shown for the Oxford Clay Formation (OXC_w).

(4) The $f_{p,\mu}$ coefficient for each geological formation varied slightly with plasticity index, consistent with (f_1) coefficients in other mudstone strata such as London Clay (Stroud 1974, 1989; White *et al.* 2019). However, the f_p coefficient for individual SPT and triaxial pairs showed a large dispersion from the trend. Therefore, while it may be acceptable to use formation specific coefficients for the weathered clays that were considered at these sites (as in the first conclusion), the evidence from this study does not support the use of model coefficients based on plasticity index.

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