Introduction

The accuracy and reliability of SoilSafe Advance Continuous Surface Wave (ACSW) testing data has been reviewed in detail in SoilSafe Guidance Note SSGN009. Here it was noted that ACSW testing measures stiffness in the very small-strain linear region of the strain stiffness response curve (*see Figure 1 below*). This has the advantage of providing a reference stiffness value which can be readily adjusted for design strain levels.

Indirect indicators of stiffness derived from a range of geotechnical tests are often used for geotechnical design for reasons of cost, or practicality in the absence of alternatives. The accuracy of these empirical relationships is influenced by the sensitivity of the indicator test to stiffness and the amount of data which has been used to develop the relationship with stiffness for various types of geomaterials.

The dependence of stiffness on strain level is at best crudely allowed for in empirical relationships and often ignored completely. Hence assessment of stiffness using empirical relationships are generally conservative, providing some explanation for the frequent unreliability of many routine estimations of ground movement when based on empirically derived stiffness data.

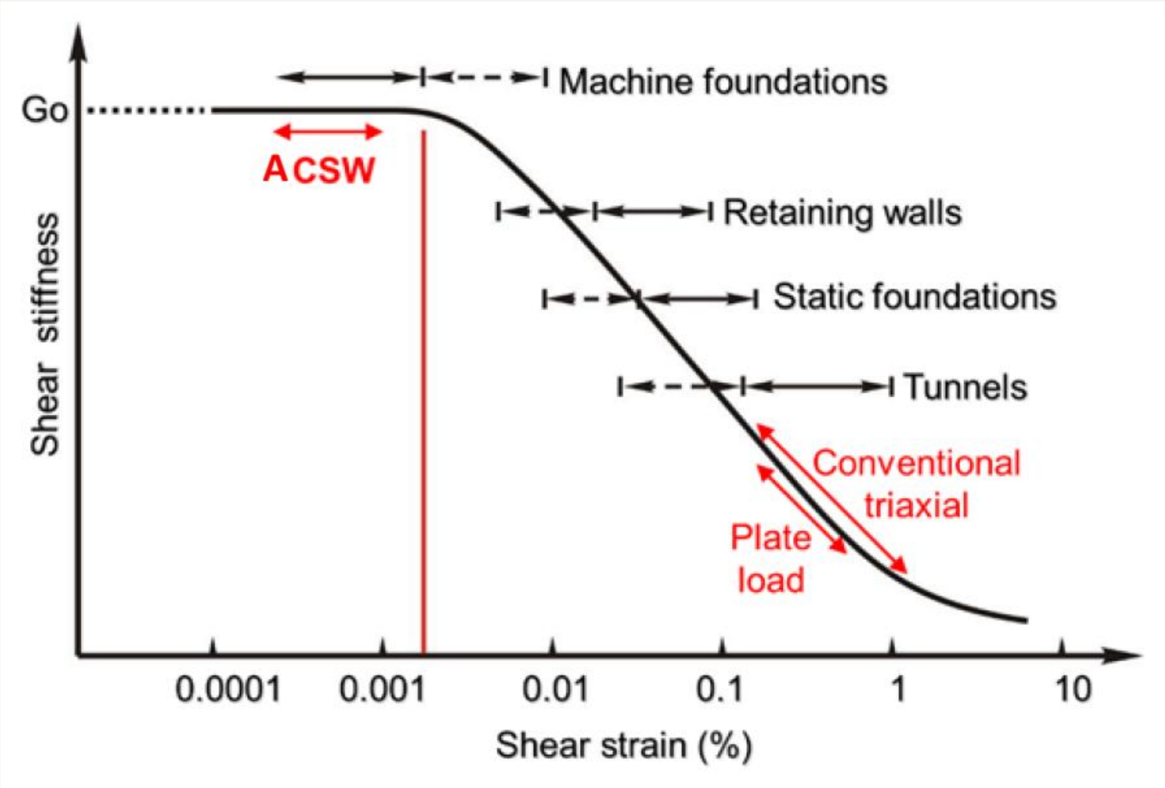
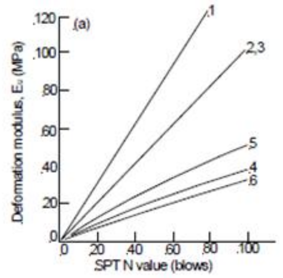


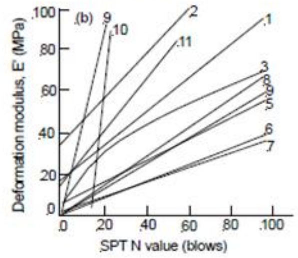
Figure 1 Typical strain stiffness response of soils showing strain levels associated with common geotechnical problems

SPT (N Value Stiffness Relationships)

Clayton (1995) discusses stiffness relationships with Standard Penetration Test (SPT) N value in detail in the CIRIA 143 publication. Figure 2 below demonstrates the wide range of variation in the relationship between stiffness and SPT N value for differing soil types when no account of strain level is taken.



	Reference – graph a	*Correlation method*
1.	Clays (Ohya et al.1982)	Lateral load tester
2.	Mudstone (Tsuchiya and Toyooka 1982)	Pressuremeter
3.	Mudstone (Leach and Thompson 1979)	Pile tests
4.	Alluvial clays (Tsuchiya and Toyooka 1982)	Pressuremeter
5.	Glacial clays (Tsuchiya and Toyooka 1982)	Pressuremeter
6.	Clays and sands (Webb 1970)	-



	Reference – graph b	*Correlation method*
1.	NC sand (D'Appolonia and D'Appolonia, 1970)	-
2.	OC sand (D'Appolonia and D ' Appolonia, 1970)	Driven piles
3.	Dry sand (Denver, 1982)	Screwplate/ pressuremeter
4.	Sand (Schultze and Menzenbach, 1961)	-
5.	Saturated sand (Webb, 1970)	-
6.	Sands (Ohya et al., 1982)	Lateral load tester
7.	Alluvial sands (Tsuchiya and Toyooka, 1982)	Pressuremeter
8.	Glacial sands (Tsuchiya and Toyooka, 1982)	Pressuremeter
9.	Sand (Komornik 1974)	Driven piles
10.	Sand (Christoulas and Pachakis, 1987)	Driven piles
11.	Sands (Yamashita et al., 1987)	Driven piles

Figure 2: Examples of correlations between equivalent drained and undrained modulus values and SPT penetration resistance, N, for mudrocks, clays and granular soils (from CIRIA 143 Fig 38)

To improve the correlation for granular soils Stroud (1989) attempted to account for strain level by plotting the ratio of E'/N_{60} as a function of degree of loading, as shown in Figure 3. It can be seen that the ratio of E'/N_{60} may rise from 1 to 2 MPa for normally consolidated sands and to 16 for over consolidated sands and gravels depending on degree of loading (q_{net}/q_{ult}).

It should be noted, however, that considerable data manipulation was required to produce the relationship shown in Figure 3, with associated uncertainty and use of the relationship requires assessment of ultimate bearing capacity (q_{ult}) which is itself subject to significant uncertainty.

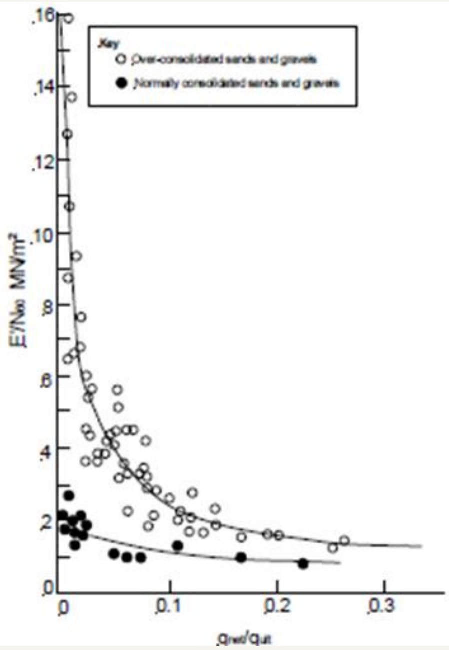


Figure 3: Relationship between stiffness, penetration resistance and degree of loading for sand (after Stroud 1989, from CIRIA 143 Fig 39)

Use of the correlations between G_{max} (G_0) and N presented CIRIA 143 Table 10 (*see Table 1 below*) also provides significant variation in small strain shear stiffness values determined. For example, the calculated range for an alluvial clay with N=10 being between 82MPa (G=16N($_{0.71}$)) and 117MPa (G=10.4N($_{1.07}$)).

Table 1: Comparison of some correlations between Gmax and SPT N value (from Crespellani and Vannucchi, 1991 from CIRIA 143 Table 10).

Soil Type		a	b	r
Clay	Alluvial	10.4	1.070	0.500
	Alluvial	17.3	0.607	0.715
	Glacial	24.6	0.555	0.712
	Alluvial	16.0	0.710	0.921
Sand	Alluvial	12.3	0.611	0.671
	Glacial	17.4	0.631	0.728
Gravel	Alluvial	8.1	0.777	0.798
	Glacial	31.3	0.526	0.552

One of the most commonly used design tables for assessing the stiffness of granular soils from SPT N values is CIRIA 143 Table 11 (see Table 2 below) which adjusts the E'/N ratio for N value. However again a wide range, even within the mean values, is evident.

Table 2: Drained Young's modulus (E') derived from Burland & Burbridge's Is values for SPT N value (from CIRIA143 Table 11).

SPT N Penetration resistance (Blows/300mm)	E'/N (MPa) at		
	Mean	Lower Limit	Upper Limit
4	1.6-2.4	0.4-0.6	3.5-5.3
10	2.2-3.4	0.7-1.1	4.6-7.0
30	3.7-5.6	1.5-2.2	6.6-10.0
60	4.6-7.0	2.3-3.5	8.9-13.5

For cohesive soils, Stroud (1975) gives the following relationship between SPT N value and the coefficient of volume compressibility:

$m_v=1/E_{oed}$): $m_v=1/(f_2 \times N)$

where f_2 ranges from 350 to 750kN/m^2 depending on the plasticity index (PI) of the clay.

Whilst knowledge of the clay's PI allows a value of f_2 to be selected with some confidence from the design line, this belies the considerable scatter in the results from various clay types and range of PI values typically determined.

In conclusion, all the available empirical stiffness relationships with SPT N value are associated with significant ranges of values. Given the relatively small range of possible N values (1 to 50), and the issues associated with undertaking and evaluating the N values recorded, considerable further potential variability is possible particularly for low N values (choosing an N value of 2 as opposed to 1 would for example result in a further 100% variation). The limitations above are greatly compounded by the absence of any adjustment in SPT N value/stiffness relationships for the strain-softening behaviour of most soils. Consequently, stiffness values for clays derived from SPT N values can frequently be an order of magnitude different from the values associated with the true design strains. The limitations in the use of SPT data for defining stiffness parameters is confirmed by BS5930:2015 which states that inferred soil parameters from SPT results 'are at best approximate' and any correlations 'should be made with great care'.

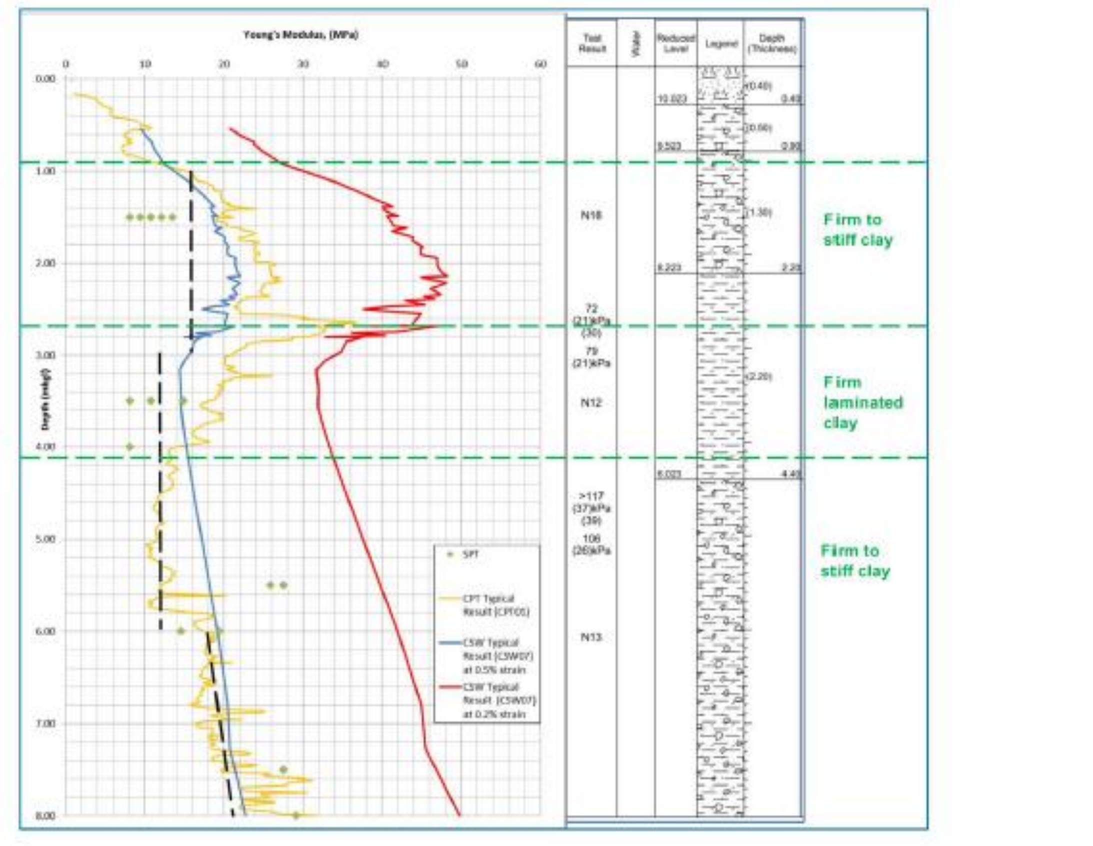


Figure 4: Comparison of typical ACSW derived stiffness profile (simple inversion) against values derived empirically for CPT and SPT data at Blyth Converter station (from Reynolds, Suttill & Milne, *in preparation*)

The limitations of SPT data are visible in Figure 4, where little evidence of a softer layer of Laminated Clay was apparent from SPT results, though identified by CPT data albeit indicated at a lower stiffness than determined from the non-intrusive CSW data.

Shear strength stiffness relationships

The relationships for drained stiffness and undrained shear strength of cohesive soils is given as E_u/C_u ranging from 150 to 1500 depending on PI value and OCR (see Figure 5 below). Due to the difficulty in determining representative values, conservative lower bound values are frequently selected. The inaccuracy of the relationship is compounded by difficulties in measuring representative Cu values due to issues of representativeness, scale and disturbance of samples used, particularly for low shear strength soils.

Again, as with empirical relations with SPT N, the limitations above are greatly compounded by the absence of any adjustment for the strain-softening behaviour of most soils.

Cone Resistance Stiffness Relationships

Cone resistance (q_c) has been related to oedometer stiffness (E_{oed}) as $E_{oed} \approx \alpha q_c$. Given that α is taken as ranging from 1 to 3, this gives a potential 100% variation from an average value of 2. However, this approach requires an interpretation of a design q_c value from the cone test data. Since qc might range from 0 to 10MPa even within an individual stratum, this could result in an order of magnitude variation on derived stiffness depending on the design value selected (*see Figure 5 for example*).

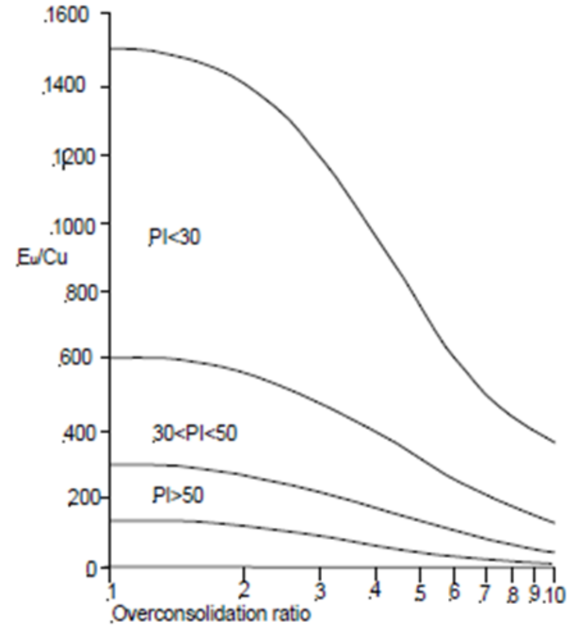


Figure 5: Correlation of Eu against Cu (after Jamiolkowski *et al, 1979)*

Summary of Comparison of ACSW Data with Empirical Stiffness Relationships

Many empirical relationships depend on obtaining representative values unaffected by sample disturbance and adopting a highly variable adjustment factor. There is limited, if any, opportunity to account for strain level, and these adjustments are at best qualitative.

Thus, orders of magnitude variation from actual stiffnesses at field strains can be expected (reflecting the inaccuracy of many traditional ground movement calculations). The potential variation in ACSW testing derived stiffness values as set out in SSGN009 are far less than the variation from empirical methods even where assumed soil parameters are utilised.

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