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Screw plate testing of a soft clay

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The screw plate test was developed for the determination of the *in situ* deformability characteristics of both granular and cohesive soils. This paper examines several theoretical models that may be used to evaluate the *in situ* undrained deformability and shearing strength characteristics of a cohesive soil medium from results of screw plate tests. It is shown that the undrained modulus and the undrained shearing strength can be evaluated directly from the load–displacement response obtained from the screw plate test.

L'essai de plaque vissée a été mis au point pour permettre la mesure des caractéristiques de déformation *in situ* des sols pulvérulents et cohérents. L'article présente un examen de plusieurs modèles théoriques qui peuvent être utilisés pour évaluer la déformabilité et la résistance au cisaillement non drainé *in situ* dans un sol cohérent à l'aide de l'essai de plaque vissée. On montre que le module non drainé et la résistance au cisaillement non drainé peuvent être obtenus directement de la loi charge–déplacement définie lors de l'essai de plaque vissée.

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Introduction

It is generally recognized that sampling disturbances can introduce considerable errors in the laboratory estimation of geotechnical properties of sensitive cohesive soils (Eden 1970; La Rochelle and Lefebvre 1970; Raymond *et al.* 1971). The degree of sample disturbance can, however, be minimized by using high-quality samplers or large block samples (Eden 1970; Domaschuk 1977; Lefebvre and Poulin 1979). Such sample retrieval procedures are by no means routine. Furthermore, the sample disturbance associated even with efficient sampling procedures constitutes an unknown factor. It is therefore advantageous to adopt *in situ* techniques for the estimation of geotechnical properties. They provide valuable means for the correlation of laboratory parameters derived from efficient sampling techniques. Comprehensive accounts of *in situ* tests (such as shallow and deep plate load tests, pressure meter tests, screw plate and other penetration tests) in both cohesive and cohesionless soils are given by Sanglerat (1972), Mitchell and Gardner (1975), Wroth (1975), Marsland and Randolph (1977), Baguelin *et al.* (1977), and Ladd *et al.* (1977). The screw plate test is a recent variation of the conventional plate load test, which has been utilized for the measurement of *in situ* geotechnical properties of both cohesive and cohesionless soils (Fig. 1). The test plate is basically a single cycle of a helical auger, which is inserted into the soil medium. Early applications of the screw plate test, as described by Kummeneje and Eide (1961), were primarily concerned with its use as a sounding device to observe the change in density of loose sand deposits due to blast effects. Further field studies of screw plate testing of granular soil deposits are

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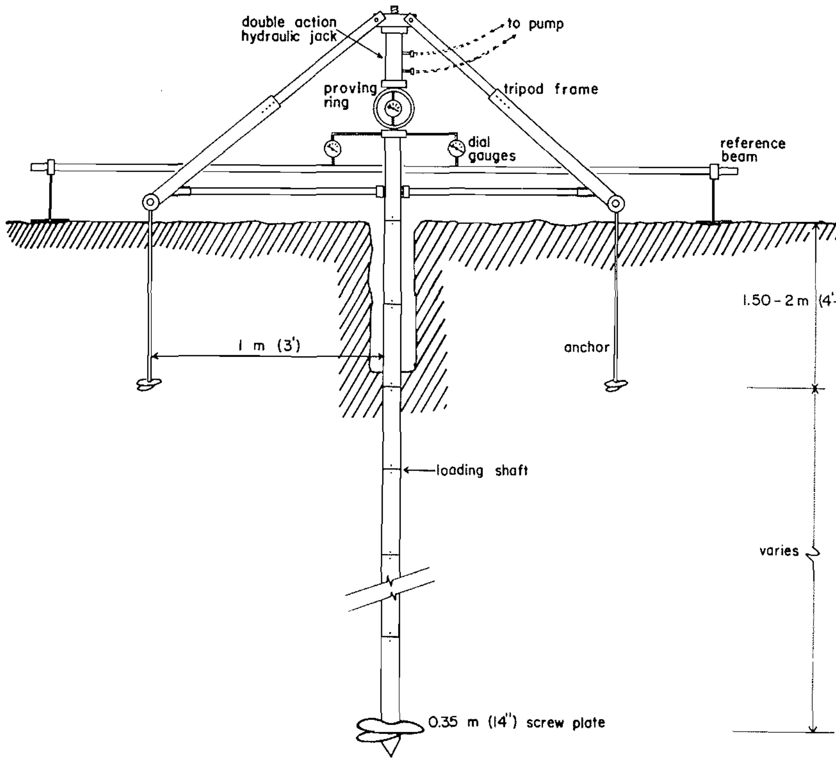

FIG. 1. Schematic view of the Carleton University screw plate device.

reported by Gould (1967). Schmertmann (1970) and Janbu and Senneset (1972) have used the screw plate test to measure the *in situ* deformability characteristics of cohesionless soil deposits. Dahlberg (1975) has used the test to ascertain the influence of precompression on the deformability of granular soils. More recently, studies involving time-independent and time-dependent screw plate testing of silty clays were reported by Schwab (1976) and Schwab and Broms (1977).

Since the primary application of the screw plate test has been extensively concerned with testing in granular soil deposits, the interpretation of the test results invariably involved empirical assumptions. The empiricism that is usually associated with the treatment of settlement and deformations in granular soils (Sutherland 1975; Burland 1977) has therefore prompted the use of similar relationships for the estimation of "moduli of deformation" from screw plate tests. When dealing with screw plate tests conducted in cohesive soils, the deformability and strength characteristics can be estimated by recourse to certain simplified theories of material behaviour, such as linearized elasticity and ideal plasticity. Such theories provide useful descriptions of the undrained response of cohesive soils at working and ultimate load levels. Furthermore, since the geotechnical parameters predicted by such theories are invariant material properties the results from various *in situ* tests (such as screw plate and pressure meter tests) permit comparison.

This paper presents the results of some preliminary screw plate tests conducted at the Gloucester test fill site (Bozozuk and Leonards 1972). The performance of the screw plate test is examined in the light of the classical theories of isotropic elasticity and ideal plasticity. The relationships proposed here can be utilized to determine the undrained elastic modulus and the undrained shear strength of a cohesive soil from the load–displacement results measured in a screw plate test.

The Undrained Modulus from Screw Plate Tests

The screw plate, like any other penetrating *in situ* testing device, causes some soil disturbance during its installation. The extent of this soil disturbance can be quantified only in rare cases. The stress paths associated with either the alteration of the *in situ* state of stress or the nonhomogeneity created by the altera-

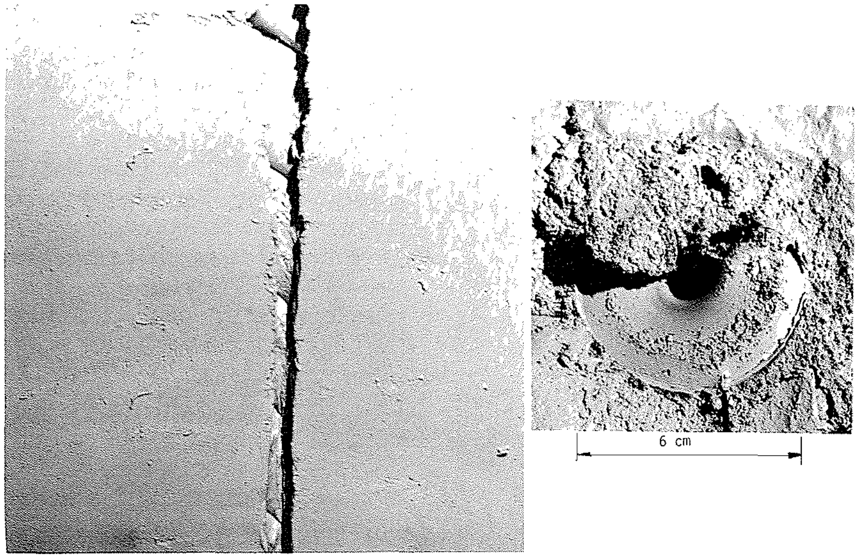

FIG. 2. Driven path of a model screw plate in compacted kaolin.

tion of material characteristics along the driven path of the test device are open to conjecture in any form of *in situ* testing. With regard to the screw plate test, these soil disturbances are probably no more severe than the penetration action of the Camkometer (or similar device) in an otherwise unlined borehole. Laboratory studies (Selvadurai *et al.* 1980) conducted with a model screw plate inserted into a stratum of compacted kaolin indicate that there is no severe straining of the compacted material due to the penetration action of the helical plate (Fig. 2). These effects can be minimized by assigning suitable proportions to the diameter of the loading shaft ($2c$), the diameter of the screw plate ($2a$), the thickness of the plate (t), and the pitch ($2b$). (For example, in the investigations performed the various aspect ratios were: $c/a \simeq 0.125$; $b/a \simeq 0.25$; $t/a \simeq 0.02$.) After insertion to the required depth, the screw plate load test will examine a region of the soil that is relatively unaffected by the driving action. Also, during the driving of the screw plate there is little or no stress relief by any process similar to the removal of overburden stresses.

The above considerations associated with the soil disturbance, together with other factors relating to conditions at the soil – screw plate interface, the flexibility of the plate, and the helical nature of the test plate, etc., make it necessary to consider a catalogue of plausible theoretical models from which the undrained *in situ* deformability characteristics can be inferred. These results discussed in this section are derived from (i) exact mathematical solutions, (ii) approximate solutions based on variational methods, and (iii) finite element solutions. From these investigations it becomes evident that certain bounds can be assigned for the *in situ* undrained modulus as inferred from the results of screw plate tests. A full account of the theoretical developments is given by Selvadurai and Nicholas (1979).

A theoretical problem concerning the estimation of the undrained deformability characteristics from the results of screw plate tests can be formulated as an axisymmetric problem in the classical theory of elasticity, where a circular plate-like region embedded in a homogeneous isotropic elastic medium is subjected to an axial load. In such a theoretical development the following factors should be given due consideration.

(i) The Elastic Medium

In the theoretical developments, the screw plate is assumed to be located in an elastic medium of infinite extent. This is due to the fact that the screw plate test is usually carried out at a depth substantially greater than the diameter of the plate; available theoretical results (Butterfield and Banerjee 1971; Hunter and Gamblen 1974; Selvadurai 1978) indicate that when the test plate is located at a depth greater than 6–8 diameters, the effect of the free boundary on the deflection of the plate is almost negligible. Practical considerations would indicate that screw plate tests carried out near ground level are essentially plate load tests.

(ii) The Test Plate

The circular area over which the applied loads are transmitted to the cohesive soil may be assumed to

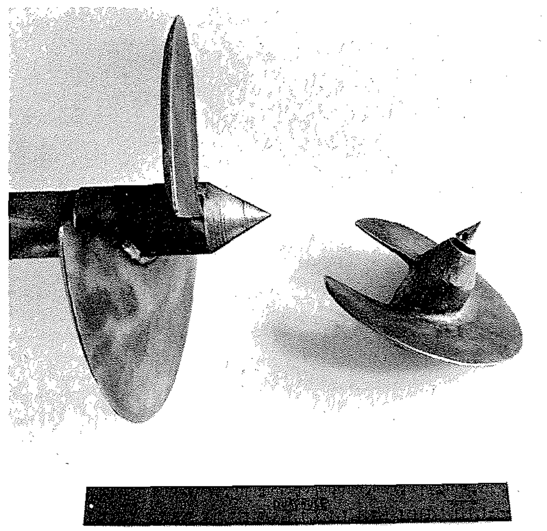

FIG. 3. Screw plates used in field testing.

be completely flexible, infinitely rigid, or possessing finite flexural rigidity characteristics commensurate with the plate dimensions and its elastic characteristics. The effect of the helical nature of the test plate may also have an influence on the effective plate dimensions (Fig. 3). In this instance the behaviour of the test plate may be approximated by that of a rigid spheroidal region embedded in the elastic medium.

(iii) The Soil–Plate Interface

In practice the interface between the soil medium and the screw plate can exhibit a variety of interface phenomena ranging from complete adhesion (or bonded) to the completely frictionless (or smooth), with Coulomb friction or finite friction occupying an intermediate position. The analysis of the latter class of effects is mathematically complex. For example, the analysis of elastic contact problems, which exhibit frictional interface phenomena with finite frictional forces, can be obtained via an incremental analysis (see, e.g., de Pater and Kalker 1975). The results corresponding to perfectly bonded and smooth interfaces therefore provide probable limits for the assessment of screw plate test results. In addition it is also possible to visualize a situation wherein bonding exists only on one plane face of the screw plate and the other detaches itself from the soil region.

(iv) Soil Disturbance

As discussed previously, the driving action of the screw plate causes, by its cutting action, a certain degree of soil disturbance. The influence of this disturbance on the measured *in situ* deformability characteristics can be assessed by adopting the finite element method. In the extreme case it is assumed that the extent of soil disturbance is such that the cylindrical column of soil along the driven path of the screw plate possesses zero stiffness. In this instance, the screw plate test degenerates to a plate load test carried out at the base of an unlined borehole.

Estimates for the Undrained Elastic Modulus E_u

The numerical results derived from the various theoretical models of the screw plate performance are summarized in Table 1. From these results it becomes evident that bounds can be established for the estimation of the *in situ* undrained modulus from results of screw plate tests. For the undrained elastic behaviour of the cohesive soil medium, the range of $E_u w/pa$ (where w is the plate settlement; p is the applied

TABLE 1. Estimation of undrained modulus from screw plate tests

Solution	$\frac{w}{pa/E_u}$	Reference	Remarks
(a)	0.630	Kelvin (1890)	Average displacement of uniform load
(b)	0.589	Collins (1962), Kanwal and Sharma (1976), Selvadurai (1976)	Displacement of fully bonded rigid disc
(c)	0.750	Hunter and Gamblen (1974)	Displacement of smoothly embedded rigid disc
(d)	0.750	Keer (1975)	Displacement of partially bonded rigid disc
(e)	0.648	Selvadurai (1979*a,b*)	Central displacement of flexible disc*
(f)	0.585	Selvadurai (1976)	Displacement of rigid spheroidal region†
(g)	0.730	Christian and Carrier (1978), Pells and Turner (1978)	Average displacement of deep borehole subjected to uniform load
(h)	0.525	Christian and Carrier (1978), Pells and Turner (1978)	Displacement of rigid plate at base of deep borehole

NOTES: a is radius of screw plate; p is average stress on screw plate $= P/\pi a^2$; E_u is undrained modulus.

*Relative rigidity of plate

$$R = \frac{\pi(3-4\nu)(1+\nu)}{12(1-\nu_p)(1-\nu)}\frac{E_p}{E}\left(\frac{h}{a}\right)^3 = 10$$

where h is thickness of screw plate; and E_p, ν_p are the elastic constants for the plate material.

†Screw plate of half pitch to diameter ratio of 0.125.

stress; a is the radius of the screw plate; E_u is the undrained elastic modulus) applicable for the screw plate test varies from 0.750 to 0.525. Both these results relate to physically admissible interpretations of the screw plate test performance. The lower limit admits a situation where there is complete loss of soil strength and stiffness along the driven path of the screw plate (such a situation could conceivably occur if the screw plate were power driven into a deposit of highly sensitive clay). In the authors' opinion, however, this assumption is perhaps too stringent a restriction on the performance of the screw plate test. The remaining set of theoretical models provides the following approximate result for the assessment of the *undrained deformability characteristics* of a cohesive soil medium from results of screw plate tests:

[1] $w/(pa/E_u) \simeq 0.60\text{–}0.75$

The accuracy and reliability of the above estimates can be established only by recourse to comparison with equivalent results derived from other *in situ* tests such as the pressure meter test or from laboratory tests conducted on relatively undisturbed samples of the cohesive soil medium. Unlike the previous investigations of the screw plate test (Janbu and Senneset 1973; Dahlberg 1975; Schwab 1976; Schwab and Broms 1977) the above result places the estimation of E_u from screw plate tests on a sound theoretical footing (at least within the assumptions of idealized linear elastic behaviour), thereby providing a basis for comparison with results of modulus values derived from other classes of *in situ* tests such as the pressure meter test.

The Undrained Shear Strength from Screw Plate Tests

This section presents a theoretical basis for the estimation of the *in situ* undrained shear strength of the cohesive soil (c_u) from the ultimate load recorded in the screw plate test. As has been observed by Schwab (1976) and Schwab and Broms (1977) the effect of sinkage of the screw plate is to make the failure load less discernable. To eliminate this ambiguity in the definition of the limit load it is convenient to adopt a modified plot of the load–settlement curve for the screw plate test wherein the average stress is plotted in a logarithmic scale and the plate settlement is expressed as a percentage of the plate diameter. A failure load can then be defined as either the peak value of the modified pressure–settlement curve or the pressure at which the slope of the load–settlement curve changes abruptly. The failure load (P_{ult}) recorded is related to the undrained shearing strength of the cohesive soil by appeal to theoretical solutions based on ideal plasticity. Table 2 summarizes a set of parameters for p_{ult}/c_u (where $p_{ult} = P_{ult}/\pi a^2$) that may be utilized to estimate c_u. For example, the results by Shield (1955) and Eason and Shield (1960) are based on classical plasticity solutions that invoke the Harr – von Karman postulate (i.e., the circumferential stress $\sigma_{\theta\theta}$ in the axisymmetric problem is set equal to the algebraic value of one of the principal stresses derived from the stress system σ_{rr}, σ_{zz}, and σ_{rz}). Also in the case of a purely cohesive soil, the Mohr–Coulomb yield condition can be identified with the Tresca yield condition. The result of Meyerhof (1951) is based on Hencky's approximate method involving a plane strain slip-line field. Skempton's (1951) result is developed for the analysis of deep circular foundations. It may be observed that these results essentially correspond to the loading of a circular plate at the base of an unlined borehole. The results by Selvadurai and Szymanski (1980) are also based on classical plasticity solutions developed for smooth and rough circular rigid anchor plates embedded in a cohesive soil medium. Here again, the Harr – von Karman postulate ($\sigma_1 = \sigma_2 = \sigma_{\theta\theta}$) is invoked to render the problem statically determinate. In this discussion only a few solutions based on idealized plastic behaviour have been examined; other solutions developed for cavity expansion problems could no doubt find useful application.

Estimates for the Undrained Shear Strength c_u

Considering the theoretical results given in Table 2

TABLE 2. Estimation of undrained shear strength from screw plate tests

Solution	p_{ult}/c_u	Reference	Remarks
(a)	5.69	Shield (1955)	Rigid circular punch on half-space—smooth interface
(b)	6.05	Eason and Shield (1960)	Rigid circular punch on half-space—rough interface
(c)	9.00	Skempton (1951)	Circular foundation at large depth—empirical
(d)	9.34	Meyerhof (1951)	Circular foundation at large depth—approximate solution—rough interface
(e)	10.97	Selvadurai and Szymanski (1980)	Deeply embedded rigid circular plate—smooth interface
(f)	11.35	Selvadurai and Szymanski (1980)	Deeply embedded rigid circular plate—rough interface

NOTES: p_{ult} is failure stress; c_u is undrained shear strength.

it is evident that the solutions (a) and (b) are of limited interest in the estimation of c_u from screw plate tests. These solutions are presented only for purposes of comparison. Furthermore, these solutions, developed for the ideally plastic half-space problem, disregard the shear strength that can be mobilized in the upper half-space region (i.e., the region located above the plane of the screw plate). A comparison of (a) and (b) with (c)–(f) clearly indicates the significance of the contribution of the upper half-space region to P_{ult}. The theoretical solutions (c)–(f) give the following bounds for the assessment of the *undrained shear strength* of a cohesive soil medium from the ultimate load derived from a screw plate test:

[2] $p_{ult}/c_u \simeq 9.00–11.35$

Field Studies

This section describes the results of some preliminary screw plate tests conducted at a test fill site adjacent to the Canadian Forces Station (CFS) Gloucester, near Ottawa, Ontario. The test fill constructed at this site has been the subject of extensive field and laboratory investigations (see, e.g., Bozozuk and Leonards 1972; Lo *et al.* 1976). The screw plate tests were carried out at a location approximately 10 m from the edge of the fill and in the vicinity of the minor central axis of the fill (see Fig. 4). Briefly, the soil profile of the site in this region (Fig. 4) consists of a surface crust terminating abruptly at a depth of approximately 1.8 m with the lower 0.9 m composed of a medium-stiff fissured clay. The crust rests on a soft silty clay layer of thickness approximately 0.75 m containing organic matter. The underlying grey silty marine clay extends to a depth of approximately 18 m. A more complete account of the index properties of the various strata, together with their *in situ* undrained shear strength characteristics, may be found in Bozozuk and Leonards (1972). In addition, the above authors report results of undrained modulus measurements carried out on very high-quality triaxial samples obtained with the Norwegian Geotechnical Institute (NGI) and Osterberg samplers. These results indicate that, for the deep deposit of grey clay, the undrained elastic modulus approximately corresponds to the empirical relationship $E_u \simeq 630c_u$ in the upper region and $E_u \simeq 1070c_u$ in the lower region. Since the screw plate tests were conducted in the upper region of the grey clay stratum (maximum depth of test 4 m) it would appear that the undrained elastic modulus as inferred from the shear strength data of Bozozuk and Leonards and the above empirical relationships

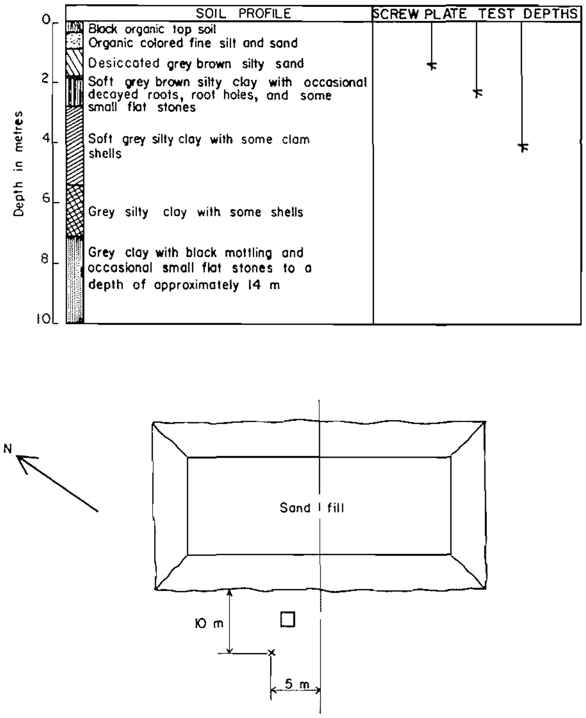

FIG. 4. Gloucester test fill site—location of screw plate tests.

would approximately correspond to (6–8) × 10^3 kPa at the 2.3 m depth and (12–15) × 10^3 kPa at the 4.1 m depth.

Two screw plate tests were performed at this site at depths of approximately 2.0 and 4.0 m. The initial metre of the organic matter was removed by a 0.2 m diameter auger to facilitate the driving of the screw plate. The screw plate was inserted into the soil medium manually. A probable ultimate load for the plate was established a priori by using the shear strength data given by Bozozuk and Leonards (1972) and [2]. The screw plate was subjected to a maximum load not greater than one third this ultimate value. Before commencement of the test the screw plate was subjected to a priming load of approximately 1.3 kN. Each subsequent load increment was maintained for a period of 2 min. The field tests performed thus far display no tendency for any accelerated creep. Figure 5 shows the typical load–displacement cycles measured for screw plates located at approximately 2 and 4 m depths, respectively. The first cycle of these load–settlement curves indicates the possibility of the occurrence of some disturbance either due to the smearing action of the driven plate or bedding errors in the test procedure. The second cycle of each screw plate test is used for the estimation of the undrained deformability characteristics of the grey clay. Fur-

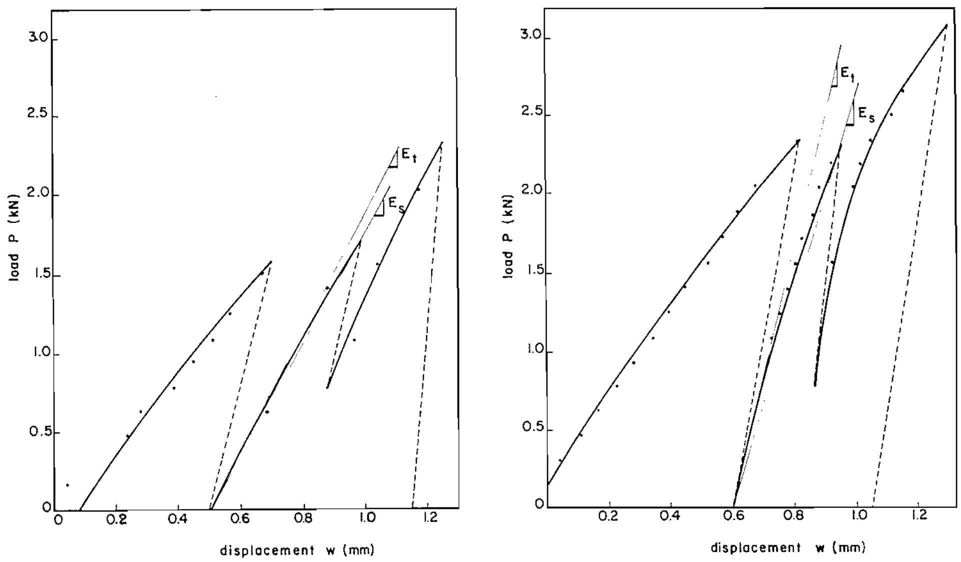

FIG. 5. Load–settlement curves for the screw plate test.

TABLE 3. Summary of results for the undrained modulus

Depth (m)	$E_u = 0.6P/\pi aw$ Tangent	$E_u = 0.6P/\pi aw$ Secant	$E_u = 0.75P/\pi aw$ Tangent	$E_u = 0.75P/\pi aw$ Secant	E_u estimated from shear strength data
2	5.0	4.5	6.1	5.6	6.0–8.0
4	13.5	9.6	17.0	12.0	12.0–15.0

NOTES: All modulus values are in units of 10^3 kPa; $E_u \simeq 630c_u$; at a depth of 2.3 m, $c_u \simeq 10$ kPa; at a depth of 4.1 m, $c_u \simeq 20$ kPa.

thermore, two sets of modulus values can be evaluated corresponding to the secant or tangent modulus for the second loading curve. A summary of these modulus values is presented in Table 3. These preliminary tests were performed with a view to estimating the undrained deformability characteristics of the soft clay. As such, the loads applied were well below those required for the determination of *in situ* values of c_u.

Conclusions

This paper outlines the possible analytical models that can be utilized to estimate, from the results of a screw plate test, the undrained modulus and undrained shear strength values of a relatively homogeneous isotropic cohesive soil medium. The theoretical formulations are used to examine the results of some preliminary screw plate tests conducted at the CFS Gloucester site. The estimates for the undrained modulus values appear to be generally in agreement with results inferred from empirical relationships based on shear strength data.

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