Shear strength parameters obtained from pressuremeter tests

Paramètres de résistance au cisaillement obtenus à partir d'essais au pressiomètre

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SYNOPSIS This paper presents a simple method of interpretation to obtain shear strength parameters from pressuremeter tests. Two sets of formulae are derived, one for the determination of the undrained shear strength based on total stresses, and one based on effective stresses to determine friction and attraction. The total stress approach is applied to offshore pressuremeter tests as well as onshore tests in clays, and the results obtained are compared with standard laboratory triaxial tests. The approach appears promising. Application of the effective stress procedure is not included due to lack of available pressuremeter data. So far the effective stress formula is valid for drained conditions only.

INTRODUCTION

The reliability of pressuremeter tests has improved since the first appearance of the instrument. Among the major reasons for this are the development of the selfboring equipment, which can provide tests with less soil disturbance, and pore pressure measurements during the tests which will lead to an evaluation based on effective stress.

A large number of instrument types exists, differing both in size and in design. However, the basic test procedure remains the same, with measurements of changes in volume and total pressure and the pore pressure at the membrane during radial expansion. For the interpretation of the shear strength parameters, there is no generally accepted procedure available at present.

During evaluation of the dyprometer tests performed at Frigg Field in the Norwegian Sector of the North Sea, the authors applied the theory of expanding cylindrical cavities to obtain shear strength parameters, by relatively simple equations (Stordal, 1982). This paper is an extract of some of the results obtained.

THEORY OF INTERPRETATION

In an elastic-perfectly plastic halfspace one assumes a vertical cylindrical cavity of radius r_i, and a length sufficient to be represented by plane strain conditions on a horizontal plane, Fig.1a.

The pressure in the cavity, p, will lead to volumetric expansion ε_v of the cavity and to variations in the radial σ_r and tangential stresses σ_θ in the surrounding soil. For plane strain, the stress equilibrium of the surrounding soil lead to the following differential equation (eg.Vesic 1972).

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\epsilon}{r} = 0 \qquad (1)$$

where r = radius from the center axes of the cavity.

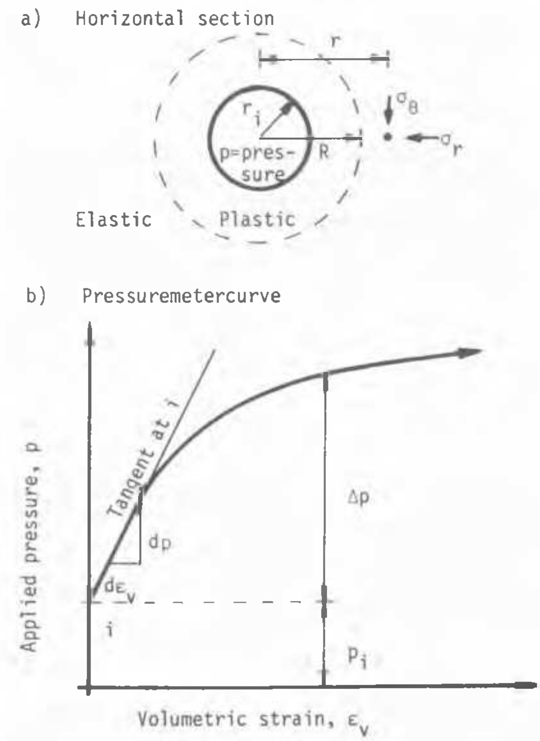

Fig.1. Notations, and pressuremeter curve, in principle.

For small deformations, the behaviour is assumed linear elastic, and since $\varepsilon_z = 0$ the stress changes become $\Delta\sigma_r = -\Delta\sigma_\theta$, leading to the strain changes

$$\Delta\varepsilon_r = -\Delta\varepsilon_\theta = \frac{\Delta r}{r_i} = \frac{1+\nu}{E}\Delta\sigma_r = \frac{\Delta\sigma_r}{2G} \tag{2}$$

Since the volumetric change is $\varepsilon_v \cong 2\Delta r/r_1 = 2\varepsilon_r$ one obtains from Eq.(2)

$$G = \frac{\Delta\sigma_r}{\Delta\varepsilon_v} = \left(\frac{dp}{d\varepsilon_v}\right)_i \tag{3}$$

because $\sigma_r \cong p$ at the boundary $r = r_i$.

Hence, the G-modulus can be determined as the tangent modulus to the pressuremeter curve, p-ε_v, near the initial condition $\varepsilon_v \cong 0$ for $\sigma_r \cong p_i$, see Fig.1b.

By increasing the cavity pressure sufficiently the soil starts to yield, and the plastified zone around the cavity will grow with increasing ε_v. The plastified zone has a radius R for a given ε_v.

In a total stress analysis the yield condition for a saturated clay may be expressed by

$$2s_u = \sigma_1 - \sigma_3 = \sigma_r - \sigma_\theta \tag{4}$$

where s_u = undrained shear strength. Hence, the differential equation becomes

$$\frac{d\sigma_r}{dr} + \frac{2s_u}{r} = 0 \tag{5}$$

for the plastified zone.

By solving the differential equations for the elastic and the plastic zones, and assuming no volume change during plastic yield, and observing the boundary conditions at the cavity boundary ($r = r_i$) and the plastic zone limit ($r = R$) one finds, when neglecting terms of second order

$$\frac{\Delta p}{s_u} = \ln\frac{\varepsilon_v G}{s_u} + 1 \tag{6}$$

$$\frac{R}{r_i} = \sqrt{\frac{\varepsilon_v G}{s_u}} \tag{7}$$

The implisit equation (6) can easily be solved for s_u longhand, or by a simple program, or by using dimensionless diagrams.

In an *effective stress analyses* plastic yield is defined by (Janbu 1973)

$$\sigma_r' + a = N(\sigma_\theta' + a) \tag{8}$$

when $\sigma_r' = \sigma_1'$ and $\sigma_\theta' = \sigma_3'$, and the shear strength τ_f is

$$\tau_f = (a+\sigma')\tan\phi \tag{9}$$

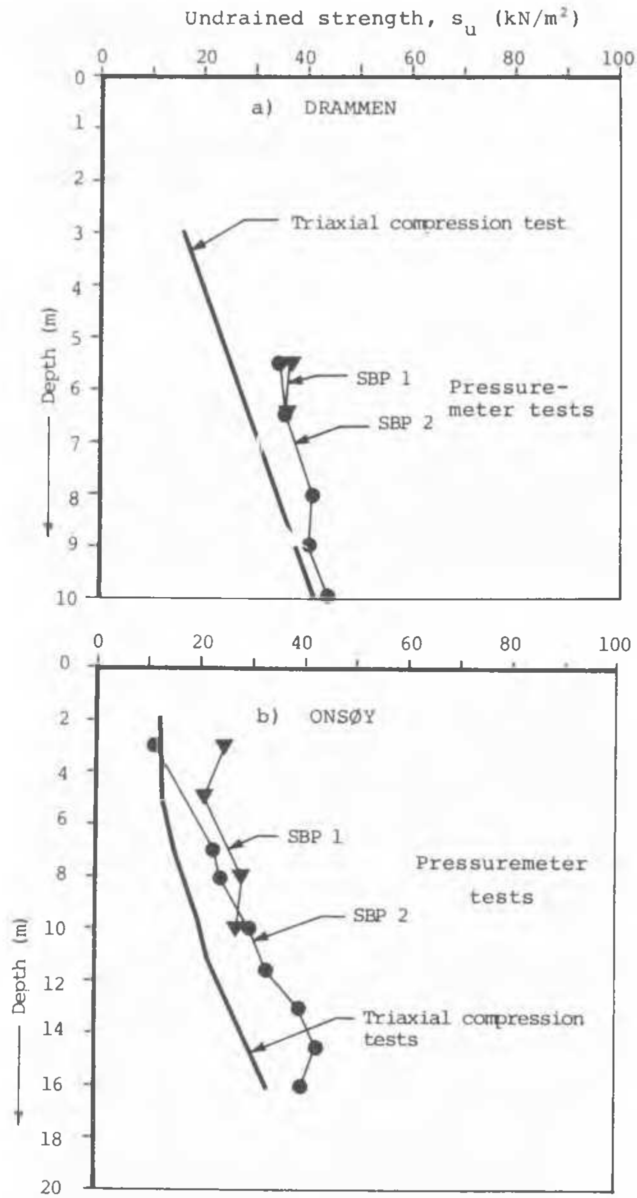

Fig.2. Undrained shear strength obtained by pressuremeters as compared to triaxial compression on two onshore sites.

where

a = attraction = $c/\tan\phi$

$\tan\phi$ = internal friction

$N = \dfrac{1+\sin\phi}{1-\sin\phi} = \tan^2(45+\tfrac{1}{2}\phi)$

When going through the same steps of derivation as described for the total stress solution one gets

$$\frac{\Delta p}{p_i'+a} = \frac{2N}{N+1}\left[\frac{N+1}{N-1}\,\frac{\varepsilon_v G}{p_i'+a}\right]^{\frac{N-1}{2N}} - 1 \tag{10}$$

and

$$\frac{R}{r_i} = \sqrt{\frac{N+1}{N-1}\,\frac{\varepsilon_v G}{p_i' + a}} \tag{11}$$

The shear modulus is equal to the tangent modulus of the pressuremeter curve for effective stress p'.

So far the solution is valid for drained conditions only, or more precisely for no excess pore pressure, ie. for du/dr = 0. For an assumed attraction Eqs.(10) and (11) can be solved for G and tanϕ through interations.

APPLICATIONS

As examples of applications, the formula and procedure presented above will be used for the interpretation of the undrained shear strength of clays, onshore and offshore. Comparisons will be made between results obtained by in situ pressurementers tests versus triaxial laboratory tests.

Onshore, the two sites are Drammen and Onsøy. The overall soil conditions have previously been published (Lacasse et al.1981). On both sites the subsoil can be described in general terms as soft to medium very slightly overconsolidated clays, with undrained strength between 10 and 45 kPa.

The summary of the results for both sites is presented in Fig.2. In both cases the in situ strengths interpreted from the pressuremeter tests are found to be larger than the triaxial compression results. Both set of results are obtained for 10% strain.

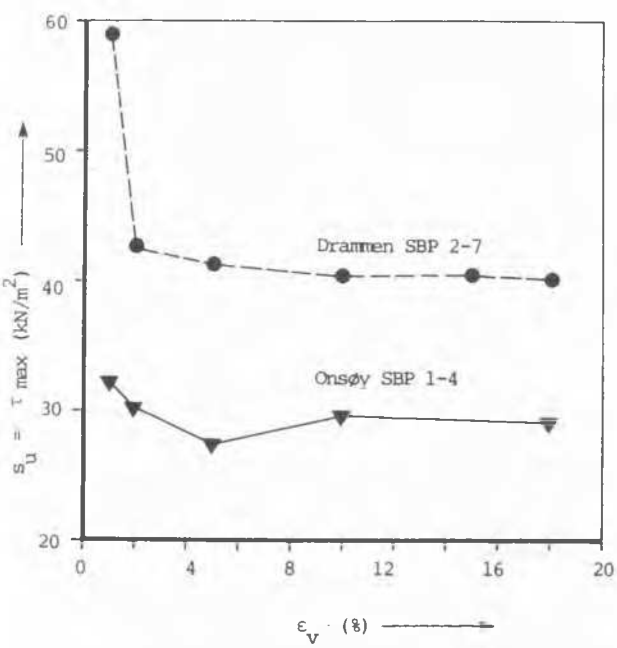

Fig.3. Influence of selected volumetric strain interpreting undrained shear strength from pressuremeter curves. Examples.

The formula for strength interpretation contain the strain levels. Hence, it is equivalent to a stress strain relationship. Therefore, the maximum shear stress can be obtained for different selected strain levels. From each of the two sites one of the stress-strain curves has been interpreted for different strains between 1% and 18%. The results, shown in Fig.3, indicate an almost ideal plastic yield over a very large range of strain levels. Therefore, for these types of clays the interpretation model based on perfectly plastic yield, seem fairly well justified.

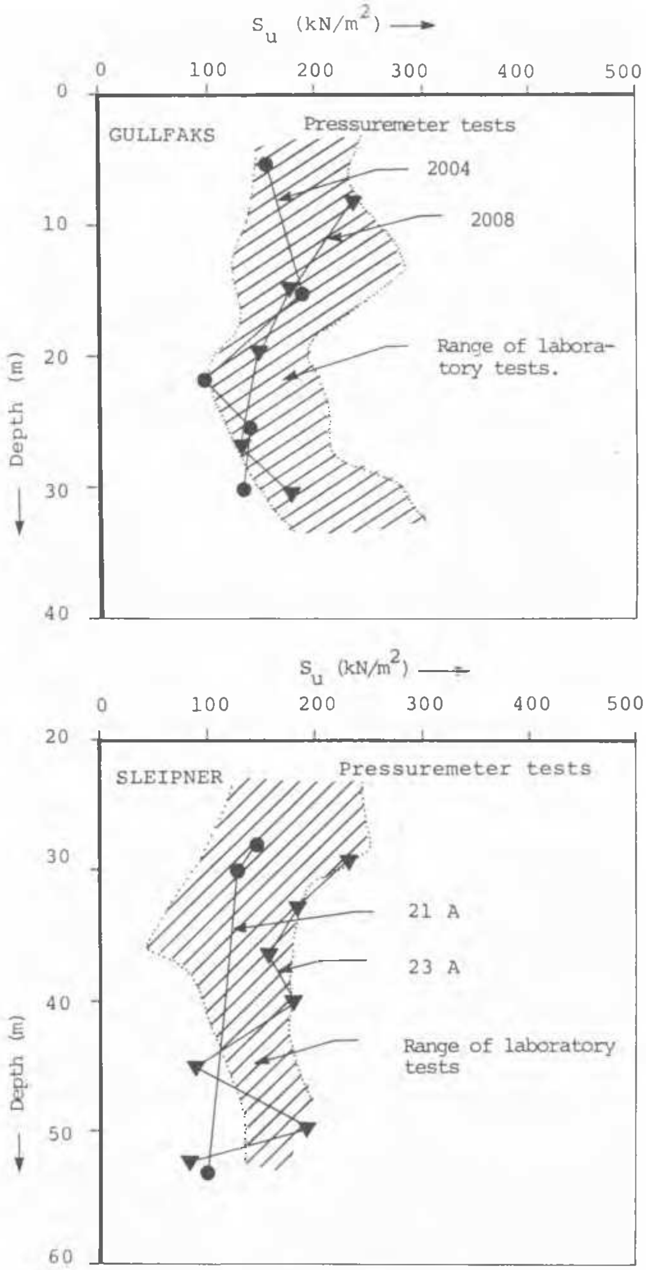

Fig.4. Pressuremeter versus triaxial test results from two offshore sites.

Offshore, the two sites selected are Gullfaks and Sleipner in the North Sea, and the applied pressuremeter data have kindly been released by Statoil and NGI for interpretation. On both sites the subsoil can be characterized in general terms as strongly overconsolidated, stiff to hard silty clays, with undrained strengths mostly in the range of 100 to 250kPa.

The results of the interpretation are included in Figs.4 and 5. The undrained strength comparisons in Fig.4 shown that the obtained in situ pressuremeter-values are located within the range of laboratory test values. There is a tendency, however, for getting somewhat lower in situ strength values for larger depths. It is not yet clear what the reasons may be. Earlier interpretations have lead to larger in situ strength also for these stiff clays (Lunne et al. 1983).

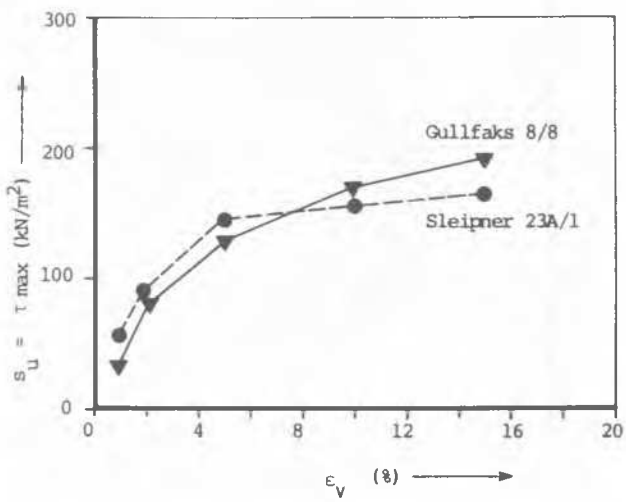

Fig.5. Influence of ε_v on the pressuremeter values of s_u.

The maximum shear stress versus volumetric strain has been obtained from one observation for each of the two sites, Fig.5. It is interesting to note that these curves are entirely different from the softer clay curves shown in Fig.2. However, the change in maximum shear for strains larger than 10% is fairly small.

The differences in ε_v-dependency, observed in Figs.3 and 5 are due to the fact that the soils are widely different, namely soft, contractant (Fig.3) versus stiff, dilatant (Fig.5).

The shear moduli obtained from the interpretation of the pressuremeter tests at Sleipner and Gullfaks are shown in Fig.6. The scatter in the results is substantial. The ratio G/s_u varies roughly between 200 and 500, with a tendency to decrease with increasing depth. The G-values are therefore somewhat lower than G_{max}, as could be expected.

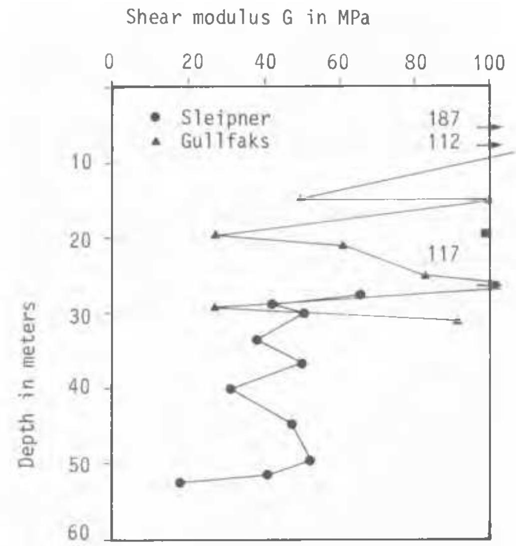

Fig.6. Shear moduli from pressure meter tests.

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