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ESTIMATION OF IN SITU LATERAL STRESSES BY FULL DISPLACEMENT METHODS

EVALUATION DES TENSIONS LATERALS IN SITU PAR DES METHODES DE DEPLACEMENT TOTAL

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SYNOPSIS: Recent developments in analytical and design methods in geotech nical engineer ing require besides others, knowledge of in-situ stress state of soil. A number of in-situ soil testing techniques have been developed by various researchers to estimate in-situ lateral stress in the soil. In this paper four methods of esti mating in-situ lateral stresses have been compared.

These methods were selected due to their simplicity and their cost-effectiveness over the other methods. One of the methods, which is based on sleeve friction from the cone penetration test, was initially proposed by the first author. The in-situ tests were performed at different sites consisting of clayey as well sandy soils. The results of a comparative study are presented in this paper.

INTRODUCTION

Various analytical and design techniques used in geotechnical engineering require knowledge of in-situ stress state of the soil. The vertical geostatic stress can be calculated with rela tively small error by determining in-situ soil unit weight; whereas the other principal component of the stress state, the lateral stress, is highly dependent on the geologic history of the soil and poses greater difficulty in its determination. If applicable, in-situ soil testing methods provide relatively quick and economical means of estimating the in-situ lateral stress at a site. Most of the in-situ testing methods require insertion of some kind of device into the ground thus changing the stress state of the soil around the device. The measured stresses, therefore, are combination of pre-insertion (in-situ) stresses and the stresses induced due to insertion effects. The stresses induced due to insertion effects depend on the existing stress state, stress history and insertion procedure. A qualitative comparison of the insertion effects produced by various in-situ soil testing devices is illustrated in Fig. 1.

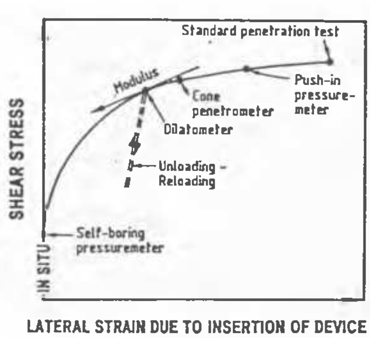

FIGURE - 1 Shear stress strain behaviour using various in-situ devices.

Analytical and empirical procedures are often adopted to estimate in-situ stresses from the measured values. The empirical methods are developed by performing the tests either in large scale calibration chambers or at sites where the stress state is al ready known. Various in-situ testing techniques developed over the years for estimation of the in-situ lateral stresses are listed in Table 1. The following four methods were selected for comparison during this research due to their simplicity and cost- effectiveness over the other methods.

i) Dilatometer

ii) Lateral stress sensing cone penetrometer

iii) Lateral stress estimation from sleeve friction

iv) Iowa stepped blade

Brief description of these test methods and the results of field tests at three sites are discussed in this paper.

EQUIPMENT AND METHODS

Dilatometer

The flat plate dilatometer was developed by Marchetti (1975) for the estimation of in-situ lateral stresses. The equipment consists of a flat stainless steel plate 94 mm wide, 15 mm thick, and approximately 235 mm long with a cutting edge in the form of a wedge with an 18 degree apex angle. An expandable thin steel membrane, 60 mm in diameter is mounted flush on the side of the plate. Complete details of equipment are given by Schmertmann and Crapps (1987).

After performing proper calibrations, the dilatometer is pushed into the ground by either quasi static penetration or by hammer ing. During this testing programme, a cone penetration rig was used for pushing the dilatometer into the ground at 20 mm/sec rate.

Once the dilatometer has been pushed to the required test depth, the vertical thrust is removed, and the membrane is inflated using compressed nitrogen. Standard practice requires two pres sure readings; the "A" reading corresponds to the pressure re quired to lift the membrane off the plate and the "B" reading corresponds to the pressure required to push the membrane 1.1 mm into the soil. After deflating the membrane, the blade is ad vanced to the next test depth. The vertical thrust required to advance the dilatometer is continuously recorded by a load cell. The test is performed at each 200 mm depth interval. The readings A and B are corrected for the membrane stiffness to determine the pressures p_o and p_1 defined by the following expression.

$$p_o = 1.05(A - Z_M + \Delta A) - 0.05(B - Z_M - \Delta B) \tag{1}$$

$$p_1 = B - Z_M - \Delta B \tag{2}$$

where

$\Delta A, \Delta B$ = calibration readings

and

Z_M = gage reading when pressure is ventilated

The pressures p_o and p_1 are used to determine the following parameters:

$$\text{Material Index, } I_D = (p_1 - p_o)/(p_o - u_o) \tag{3}$$

$$\text{Lateral Stress Index, } K_D = (p_o - u_o)/\sigma'_v \tag{4}$$

$$\text{Dilatometer Modulus, } E_D = 34.7\,(p_1 - p_o) \tag{5}$$

where

u_o = in-situ hydrostatic pore pressure

σ'_v = in-situ effective overburden pressure

A number of correlations have been proposed by various research ers for estimation of in-situ lateral stresses from the dilatome ter test (DMT). First empirical correlation (equation (6)) was proposed by Marchetti (1980) based upon a number of field tests mostly in clayey deposits.

$$K_o = (K_D/1.5)^{0.47} - 0.6 \tag{6}$$

It was observed by various researchers that the above correlation over-estimates K_o in sands (Lacasse and Lunne, 1988). Based on the results of a limited number of calibration chamber tests, Schmertmann (1983) proposed a new procedure for estimation of K_o in sands (equation (7)), which requires measurement of vertical thrust during dilatometer penetration.

$$K_o = [40 + 23K_D - 86K_D(1 - \sin\phi_{ax}) + 152(1 - \sin\phi_{ax}) - 717(1 - \sin\phi_{ax})^2] / [192 - 717(1 - \sin\phi_{ax})] \tag{7}$$

where

ϕ_{ax} = triaxial friction angle as estimated from bearing capacity theory of Durgunoglu and Mitchell (1975)

Lateral Stress Sensing Cone Penetrometer

Lateral stress sensing cone penetrometer (LSSCP) was developed at University of California, Berkeley by Huntsman (1985), to esti mate in-situ lateral stresses in cohesionless soils. The equip ment consisted of a standard electric cone penetrometer equipped with two lateral stress sensing elements which could measure normal stress of the penetrometer during penetration.

The penetrometer was modified by Tseng (1989). The new lateral stress section consists of an active ring and an inner ring, both fabricated with stainless steel. The active ring is composed of four identical arciform pieces (1.3 mm thick each) which are joined together with a polyurethane compound to form a ring with four soft seams. A cavity is created between the active ring and the inner ring which is covered with a rubber membrane and sealed at the two ends by two delrin sealing rings. The cavity is satu rated with deaired water. A strain gauged stainless steel dia phragm, 6.3 mm in diameter, is installed on the inner ring and functions as a pressure transducer. The diaphragm senses the pressure in the cavity which is induced by the surrounding pres sure on the active ring. The new design of the lateral stress section results in insignificant cross-talk between the measured lateral stress and the skin friction along the shaft. The rela tively thick active ring considerably reduces the damage poten tial. Detailed description of the penetrometer is given by Tseng (1989).

A method of interpretation of in-situ lateral stress from the lateral stress measured with the LSSCP was proposed by Jefferies et al, (1987). The method requires determination of experimental coefficients through calibration chamber testing. It is observed (Jefferies et al, 1987) that the proposed method of interpreta tion gives a poor estimate of applied lateral stress in the case of calibration chamber tests. However, lateral stresses estimated from this method for a hydraulic fill site are in good agreement with results obtained from self-boring pressuremeter tests.

Lateral Stress Estimation from Sleeve Friction

This method of estimating in-situ lateral stresses has been proposed by Masood (1990) which makes use of the sleeve friction data obtained during a cone penetration test. This method re quires sleeve friction measured with a standard electric cone penetrometer and knowledge of the stress history of the soil deposit. The proposed correla tion between the sleeve friction and the coefficient of earth pressure at rest is shown on Fig.2.

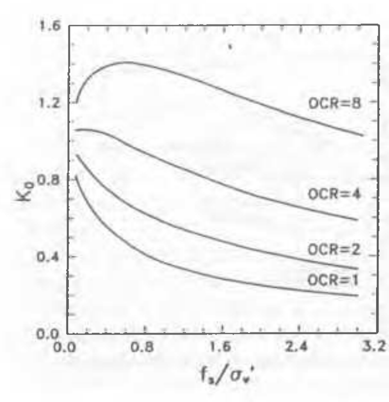

FIGURE - 2 Correlation between sleeve friction and K_o.

In order to minimise the pore pressure effects on the measured sleeve friction, use of a friction sleeve with equal end areas is recommended (Masood, 1990).

According to this method, a cone penetration test (CPT) is per formed at the site and the over consolidation ratio (OCR) of the site is also estimated. The over consolidation ratio of the soil at a site can be estimated either from the CPT data by using the method described by Masood (1990) or from the dilatometer test results. From the measured sleeve friction an estimated value of OCR, the cofficient of earth pressure at rest, K_o is estimated using Fig.2.

During this testing programme, the sleeve friction measured by the LSSCP was used for estimation of in-situ lateral stresses.

Iowa Stepped Blade

The Iowa stepped blade was developed by Handy et al (1982) to estimate geostatic lateral stresses. The blade is 64 mm wide and approximately 640 mm long. The blade thickness increases in three equal steps from 3 mm at the bottom to 7.5 mm at the top. Each step has an expandable Teflon membrane, 25.4 mm in diameter, which is connected to a control unit at the ground surface through two pneumatic tubes. More details of the equipment and its data acquisition system are given by Masood (1990). For performing a test, a hole is drilled to slightly above the test depth and then the blade is pushed into the soil by static pressure. Lift-off pressure of all the four membranes is deter mined at the same depth by sucessive pushing and inflation steps. The following expression was proposed by Handy et al (1982) for estimation of in-situ lateral stress from the lift-off pressure;

$$p_o = a p_1 e^{-bt} \qquad (8)$$

where

p_o = in-situ lateral stress

p_1 = lift-off pressure measured by blade of thickness t

a = coefficient (assumed to be 1)

b = coefficient (varies with soil type)

Schematic diagrams of the dilatometer (DMT), the lateral stress sensing cone penetrometer (LSSCP), and the stepped blade are shown on Fig.3.

TEST SITES

As a part of a research project on in-situ testing to estimate in-situ stresses of soils, the tests were contucted at the fol lowing three sites;

1. Lierstranda, Drammen
2. Museum Park, Drammen
3. Holmen, Drammen

All these sites are located near the city of Drammen, Norway and have been extensively used by the Norwegian Geotechnical Insti tute (NGI) for geotechnical engineering research purposes.

The generalized soil profiles of these sites are shown on Fig.4. Detailed information about each of the sites and the soil proper ties is given by Masood (1990).

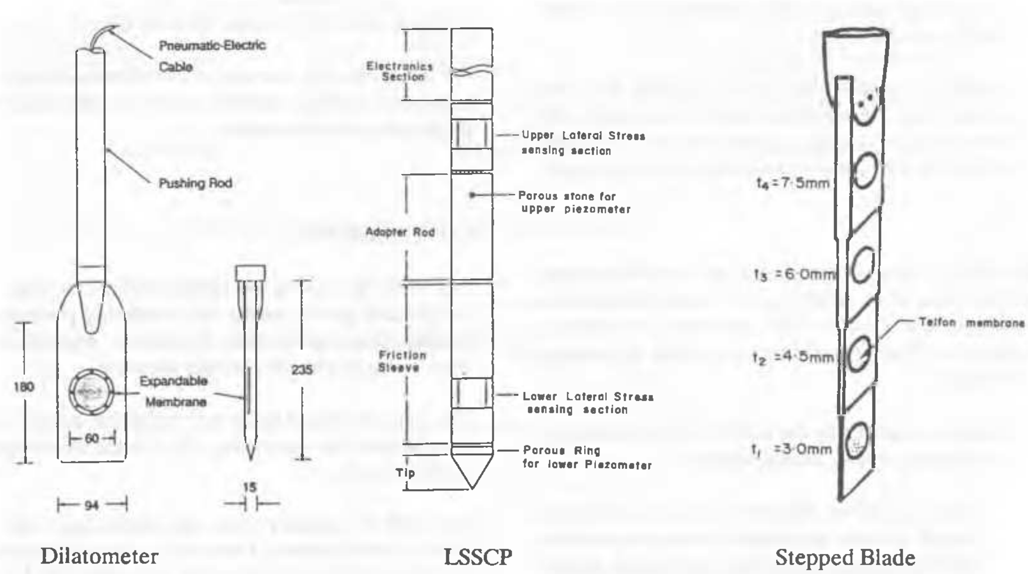

FIGURE - 3 In-situ testing devices.

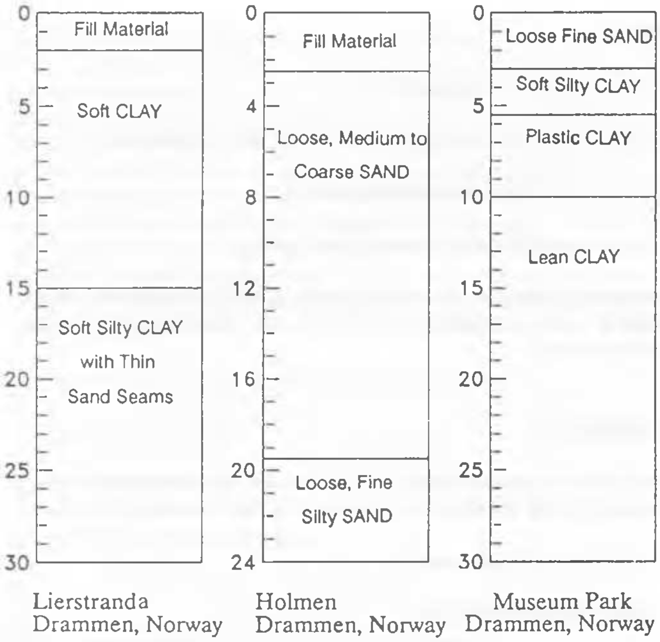

FIGURE - 4 Soil profiles at the test sites.

The soil profile at the Lierstranda site consists of 1.5 m of fill placed in 1977 overlying soft homogeneous clay to about 12 to 15m depth underlain by light brown silty clay. Some earlier studies of the site by NGI (Mokkelbost, 1988) have indicated that the in-situ pore pressures are slightly higher than the hydrostatic pressures due to incomplete consolidation of the clay layer under the fill load.

The soil profile at the Museum Park site consists of 3 to 4 m of fine to medium, loose sand overlying a 1 to 2 m thick layer of silty clay, the sulty clay stratum is underlain by about a 5 m thick layer of plastic clay above a 35 m thick lean clay layer.

The soil at the Holmen site consists of 1 to 2 m of fill mate rial underlain by 20 m thick layer of medium coarse loose sand with occasional thin layers of silt and organic matter below 3 m depth. The sand layer overlies fine silty sand deposit with thin clay layers.

FIELD TESTING

The lateral stress sensing cone penetrometer and the dilatometer were used at all the three sites. The stepped blade was used at Lierstranda and Museum Park sites. The blade was not used at Holmen site because the Teflon membranes are prone to damage during penetration in sand.

The sleeve friction values measured by the LSSCP at the three sites were also used to estimate the in-situ lateral stresses.

The lateral stresses by the LSSCP at the three sites are shown in Fig. 5 and the in-situ lateral stresses estimated by various methods are shown on Fig. 6. The following observations were made during the filed testing programme:

- The stepped blade was the most time consuming method of all the in-situ methods used due to requirement of pre drilling a borehole to the test depth.
- The rate of testing with the blade was approximately 2m /hour. The tests were performed at depth interval of 1m. The rate of testing with the dilatometer was about 8 m / hour and the readings were taken at every 200mm depth intervals. The rate of testing with the LSSCP was about 45 m /hour.
- The membranes of the stepped blade were prone to damage while pushing through sandy soils. The dilatometer membrane is relatively durable. However, penetration through gravelly soil can damage the membrane. During the testing at the Holmen site, the lateral stress section of the LSSCP was damaged by the sand particles forced in the gap between the active ring and the inner membrane.
- The dilatometer tests produced very repeatable results.

The in-situ lateral stress estimated by the various methods are compared with more reliable laboratory measurements or in-situ measurement by self-boring pressuremeter (SBPM) test as shown on Fig.6.

The stresses estiamted by the stepped blade tests were based on the value of coefficient "a" as 1. It can be observed from Fig.6 that this value of coefficient results in stresses which are quite different from values obtained by other methods.

The stress estimated by the sleeve friction method gives results which are very similar to the values estimated by laboratory tests and/or the SBPM test results.

A comparison of Figs.5 and 6 revealed that in sandy soils the lateral stress measured by the LSSCP can be related to the in- situ lateral stresses by the following correlation:

$$K_0 = 0.36 + 0.27K_c - 0.0008\, q_c/\sigma v \qquad (9)$$

Where "K_c" (termed as lateral stress cone index) is the ratio of the lateral stress measured by LSSCP to the effective over burden pressure σv and q_c is cone tip resistance.

For cohesive soils, a tentative correlation between "K_c" and "K_o" is proposed in Fig.7 which is based on the results of field testing during the current research.

CONCLUSIONS

The DMT as well as the sleeve friction method provide relatively simple and quick means of estimating profiles of in-situ later al stresses along with other important geotechnical parameters in cohesive and cohesionless soil deposits.

The use of stepped blade test is limited to soft cohesive soils and correlations for estimating "K_o" from the measured values need modifications.

The LSSCP appears to be very promising test for estimation of in-situ lateral stress. However, more experience is needed for improving the correlations for estiamting "K_o" from the measured lateral stresses.

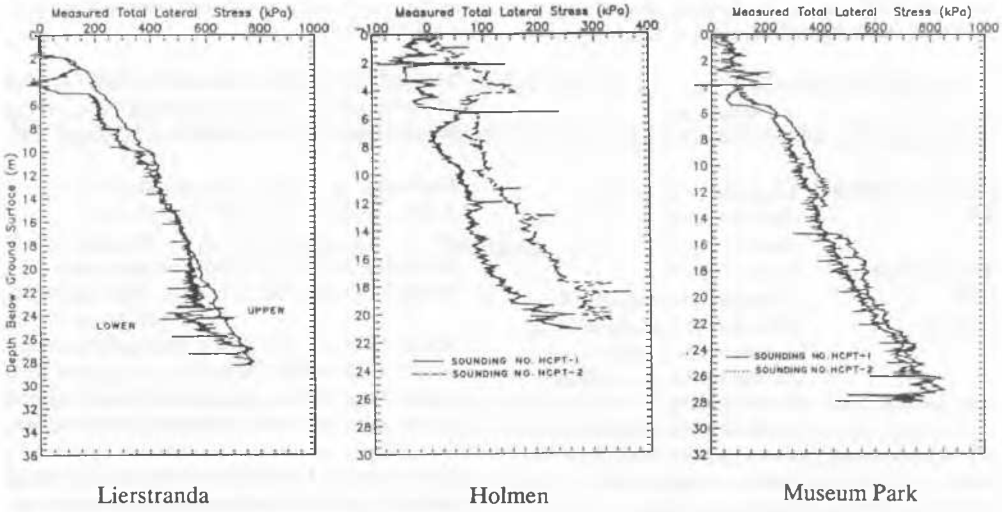

FIGURE - 5 Lateral stresses measured by LSSCP.

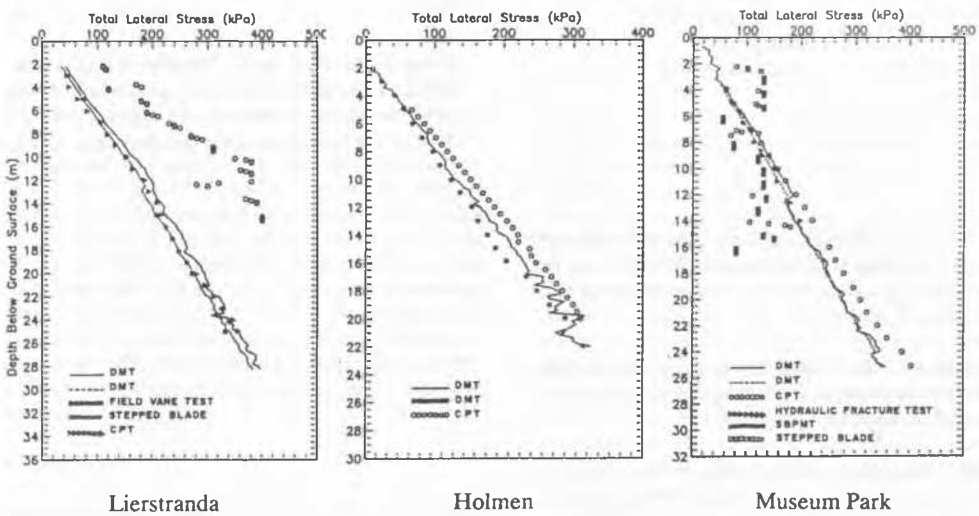

FIGURE - 6 Lateral stresses estimated by various methods.

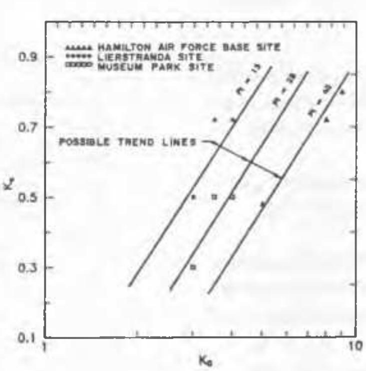

FIGURE - 7 Proposed correlation between K_c and K_o

TABLE-1 FIELD METHODS FOR DETERMININING K_o (MODIFIED FROM SCHMERTMANN, 1985)

No.	Method	Reference
1.	Menard Pressuremeter (MPMT)	Beguelin et al. (1978)
2.	Menard Geocell	Van Wanbeka & Renard (1972)
3.	Instrumented vertical Pipe	Kenny (1967)
4.	Buried Load Cells	D'Appolonis et at. (1969)
5.	Hydraulic Fracturing	Bjerrum & Andersen(1972) Bjerrum et al. (1972) Al-Shaikh Ali et al. (1981)
6.	Self-boring Pressuremeter (SBP)	Worth (1975) Clarke & Wroth (1984)
7.	Thin Pressure Plate (Glotzl spade cell)	Massarsch (1975) Tedd & Charles (1981)
8.	Flat Plate Dilatometr (DMT)	Marchetti (1980) Schmertmann (1982) Jamiolkowski et al (1985)
9.	Self-boring (SB) Load Cell	Dalton & Hawkins (1982)
10.	Iowa K_o Stepped Blade	Handy et al. (1982)
11.	Lateral Stress Sensing Cone Penetrometer	Huntsman (1985) Tseng (1989)
12.	Lateral Stress Estimation from Sleeve Friction	Masood (1990)

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