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Measurement of Swelling Pressure in the Laboratory and In Situ

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ABSTRACT

During the past 30 years more than 25 methods for the determination of the engineering characteristics of expansive soils and the prediction of heave have been proposed in the western world. Many of the proposed methods relate to laboratory or index tests whereas in situ tests, being more complex, have received less attention. Some commonly used laboratory and in situ testing methods for the determination of heave and swelling pressure are reviewed. Two instruments developed in South Africa are described, and test results are presented and compared with field loading test results. It is concluded that if sampling disturbance, size effects, selectivity in soil sampling, and simulation of actual site conditions are accounted for, laboratory and in situ test results are in good agreement.

Expansive clays are soils that exhibit unusually large volume changes as a result of moisture variations and environmental changes. The behavior of expansive soils affects the performance of structures buried in and founded on these soils; therefore, the understanding of their properties and their engineering characterization is of great importance. Engineers are well aware of the distress that lightly loaded structures, roads, runways, and utilities buried at a shallow depth in a swelling soil can suffer. The damage caused to such structures may be considerable, and rehabilitation at an early stage of a structure's life may be required, which imposes a heavy economic burden on the owner or user.

During the past 30 years more than 25 methods for the determination of the characteristics of expansive soils and the prediction of heave have been proposed in the Western world (1). However, a universally accepted method has yet to be developed. Many of the proposed methods relate to laboratory or index tests whereas in situ tests, being more complex, have received less attention. The purpose of this paper is to review some commonly used laboratory and in situ methods for the measurement of swelling pressure and heave. Two instruments developed in South Africa are described, and test results are presented and compared with some field loading test results. The relationship between laboratory

and in situ test results and field observations is discussed.

REVIEW OF SOME LABORATORY METHODS

Swelling clays exert pressure against confining stresses when water and electrolytes are available for volume increase. The swelling pressure may exceed the external stress, which will then decrease but will not prevent volume change. The relationship between applied external load and the volume change resulting from swelling of the soil is commonly used for the characterization of expansive soils. In the direct model method (2) an undisturbed sample, or alternatively a remolded sample, is placed in an oedometer and subjected to the in situ overburden pressure or the vertical stress that will exist at the end of construction. Water is then introduced to the sample and the subsequent vertical deflection is observed.

A series of swelling tests with varying initial density, moisture content, and vertical stress yields the swelling characteristic of the soil, and the following two quantitative parameters are evaluated:

1. The percentage swelling (which is the vertical swelling strain under a token load), and
2. The swelling pressure (which is the maximum vertical stress required to keep the soil sample at the initial volume when the sample is inundated with water and full swell occurs).

Many other methods for the determination of swelling characteristics using standard and modified oedometer type equipment have been developed (3-7). It has been observed that the prediction of heave using a direct model method generally underestimates the actual field heave primarily as a result of sampling disturbance.

Results of constant volume oedometer tests on an undisturbed soil are also used for heave prediction (8). An undisturbed specimen is placed in an oedometer and subjected to overburden stress. It is then flooded with water and the load is adjusted so that the specimen retains its initial volume. Once the full swelling pressure has developed, the sample is allowed to swell under reduced stress. The heave is calculated from the vertical strain occurring on the rebound curve between the constant volume condition and the post-construction pressure. Sampling disturbance is not compensated and this method also underestimates heave.

The double oedometer method (9) uses consolidation tests conducted on two nominally identical undisturbed clay samples. The samples are placed and sealed in oedometer rings under an initial token load of 1 kPa. One of the specimens is then inundated with water and allowed to swell under the token load. Both samples are then subjected to consolidation under increasing load. The stress-strain relationship for the soil at natural water content is adjusted vertically to coincide with the curve for the soaked specimen at the highest stress, and heave is then calculated from the void ratio difference between the two curves for the expected in situ effective stress change. Comparison of predicted values and field observation indicates satisfactory agreement when the method is applied under South African conditions.

The simplicity of the conventional consolidometer test has attracted the attention of many researchers and practicing engineers who use the test for the design of footings in and on expansive clay (10,11). The test data used in the design process are the coefficient of swell (and sometimes the coefficient

of consolidation), incorporated with an estimate of the in situ change in the effective stress. The coefficient of swell; that is, the slope of the swell versus log vertical stress line in the oedometer, is a useful parameter for heave prediction, as it is relatively insensitive to sampling disturbance (12).

Test data, however, do not refer directly to soil suction but to changes in effective stress in the soil from an inferred initial condition to a predicted final state. The soil suction or soil water potential is defined as the amount of work that must be done per unit quantity of pure water to transport isothermally and reversibly an infinitesimal quantity of water from a reservoir of pure water at a specified elevation and atmospheric pressure to that point in the soil under consideration. The total suction of the soil is a combination of the matrix or capillary suction, the osmotic or solute suction, and the gravitational potential. The gravitational potential is often negligible compared with the other components of the total suction. The process of swelling in situ reduces the matrix and osmotic suctions, but does not affect the gravitational potential.

Swelling tests that incorporate directly controlled suction were first performed by using a specially designed oedometer-type test cell connected to a suction pump (13). The apparatus provided only limited control of the matrix suction, however, and tests under large suction values were not attempted.

Laboratory swelling tests under indirectly controlled suction conditions may now be performed by using controlled water flow, controlled air pressure supply, reference osmotic solution, or total suction determination. In the controlled water flow method (14), a clay specimen is allowed to absorb small measurable quantities of water.

The volume change, or alternatively the resultant swelling pressure, is then related to the increase in the water content of the clay. However, the suction control is very rough and the moisture distribution throughout the clay specimen is not uniform.

In the axis translation technique (15), air pressure, applied to a soil sample, isotropically compresses both the soil particles and the water and because both are relatively incompressible, the value of the matrix suction does not change. Continuity of air spaces in the specimen is necessary to validate this assumption, which cannot be achieved when the degree of saturation is high and occluded air is contained in the soil volume.

An accurate control of suction in a clay specimen may be achieved by placing an osmotic solution in contact with the soil through a semipermeable membrane (16,17). Depending on the suction of the osmotic solution, water will flow through the membrane from the solution to the soil or vice versa. The volume change or swelling pressure that develops during this process is recorded, and, hence, the swelling characteristics of the soil are determined.

A variation of the foregoing technique is used in the membrane oedometer (18). This is a modified oedometer that places a clay sample in contact with a semipermeable membrane inside a pressure cell. The clay is subjected to controlled external loading, and matrix and solute suction. Each of these components can be varied independently to simulate in situ changes and record the corresponding strain response.

An Australian method for the prediction of surface heave is based on the membrane oedometer test (18). This method and the design method that relates to it incorporate the concepts of the direct method, axis translation, and osmotic suction control and

hence provides considerable possibilities for simulating environmental and applied stress changes.

Another way of quantitative characterization of swelling soil in the laboratory is by means of total suction determination using psychrometers (18,19) or the filter paper method (20). Psychrometers, either of the thermistor or thermocouple type, cover a wide range of total suction and are relatively inexpensive and simple to use. The relative humidity in a cavity in the soil is determined by means of the psychrometer, and total suction of the soil specimen is related to the relative humidity.

A series of psychrometer tests yields a total suction-water content relationship for a particular soil, which, in turn, can be used to calculate swell volume change. Total suction may also be determined by using the filter paper method. A disc of uniform filter paper of known dry mass is enclosed with a soil sample in a sealed container. After equilibrium has been reached, the filter paper is reweighed and its water content determined. The suction is then assessed from a suction-water content calibration of the paper.

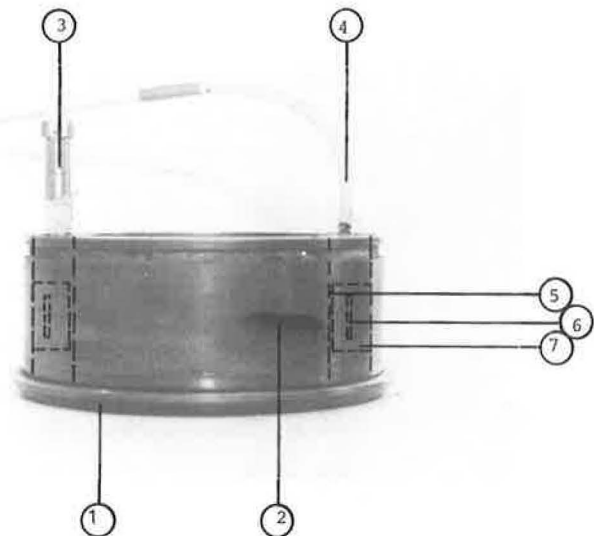
Many empirical methods have been devised for the prediction of heave and swelling pressure from index properties of the expansive soil. A method based on a correlation of plasticity index and clay fraction with the total surface heave of a soil profile has been proposed by van der Merwe (21). Another relationship between void ratio, water content, and plasticity index--the external load and the potential percent swell and swelling pressure--has been suggested by Brackley (22). In Israel a relationship between the liquid limit, dry density, water content, and potential swelling pressure has been used successfully (23,24). A comparative study of various empirical methods concluded that empirical relationships may yield unreliable predictions of swelling, and additional geological and experimental information is necessary to validate any empirical relationship when it is used in an unfamiliar situation.

All the methods reviewed so far refer to heave and swelling pressure in an uniaxial system. However, during swelling, clay exhibits anisotropic behavior, and the lateral swelling pressure may exceed the vertical pressure in many cases. The relationship between the horizontal and vertical components of stress at a point within a soil mass depends to a great extent on the stress history of the soil mass (26). Any process that involves compaction and excavation results in a change in the overconsolidation ratio (OCR) of the soil, and consequently the horizontal-to-vertical stress ratio will vary (27,28).

The lateral and swelling pressure of clay can be measured in a modified oedometer ring, and Ofer concludes that using a modified oedometer for lateral swelling pressure tests is convenient (29). A number of instruments have been developed for this purpose (29-31). An instrument of this type developed by the first author (29) is shown in Figure 1. The center section of an oedometer ring wall is trimmed to a wall thickness of 0.75 mm, and two 70 mm long strain gauges are cemented to the thin wall section at its mid-height. A casing is placed onto the ring and an airtight chamber containing a temperature compensator is formed. Swelling pressure can be measured either by measuring strain in the oedometer ring or by maintaining a null-strain condition.

IN SITU DETERMINATION OF SWELLING CHARACTERISTICS

In situ swelling tests are complex and difficult to perform, and relatively few attempts have been made to determine the swelling pressure developed in situ in clay fills or expansive soil profiles. The various



LEGEND

1. Modified oedometer ring
2. Casing
3. Air pressure inlet
4. Electrical leads
5. Thin wall section
6. Temperature compensator
7. Annular chamber

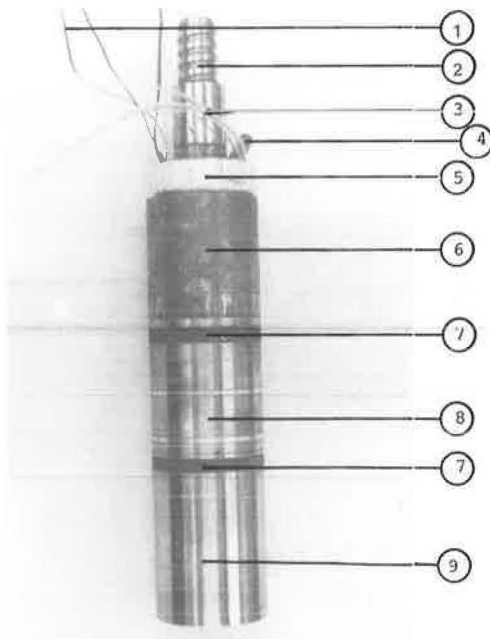
FIGURE 1 The lateral soil pressure ring.

approaches that have been tried include the determination of suction and suction changes, strain measurements on buried instrumented pipe or pile sections, and the use of pressure transducers or probe. In situ soil suction and suction changes may be measured by using tensiometers and psychrometers, which measure the low and high range of suction, respectively (20,32). These instruments are buried in the fill or soil profile at various depths, and suction readings are taken periodically in conjunction with surface heave readings. These tests, which correlate suction and surface heave, are time consuming and expensive and are valuable mainly for theoretical studies. Instrumented pipe sections (33) and instrumented piles (11,34-36) have been installed in clay, and the swelling forces that result from environmental variations have been recorded. These tests, however, are also time consuming and costly. Pressure cells buried in heaving clay with the sensitive faces vertical and horizontal have also been used to determine pressures in soil during construction and subsequent swelling (32,33,38). This method is suitable for measuring swelling pressure in fills and could conceivably also be used for measurements in undisturbed profiles.

Probe-like devices, for example, pressure meters, flat dilatometers, and the Iowa Stepped blade, have also been used to determine the in situ horizontal-to-vertical stress ratio in clay soils, either before or after swelling. These instruments, however, have not yet been developed so as to follow the swelling process and to record in situ swelling pressure as it develops.

A probe and testing technique that potentially will allow the in situ determination of lateral swelling pressure in expansive soils has been developed by Ofer (39,40). The cylindrical in situ soil pressure probe is shown in Figure 2. It has an outside diameter of 70 mm, a length of 225 mm, and consists of five modules:

1. Pressure transducer,
2. Two wetting rings,
3. Cutting edge,



LEGEND

1. Electric leads
2. Drilling rod connector
3. Water supply tubes
4. Air pressure inlet
5. Temperature compensator
6. Guard sleeve and connection head
7. Porous ring
8. Pressure transducer
9. Cutting edge

FIGURE 2 The in situ soil pressure probe.

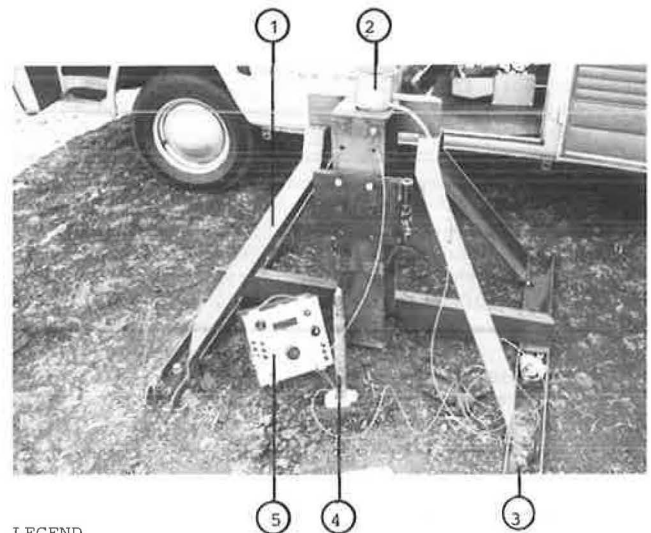
4. Temperature compensator, and
5. Connection head and guard sleeve.

The pressure transducer has a thin-walled section to which two 70 mm long strain gauges are cemented. The strain gauges are enclosed in an air-tight chamber allowing either strain or null type pressure measurements. The wetting rings are located at either end of the transducer module. Each ring has a porous section connected to a water reservoir located at the surface. The cutting edge is located below the lower wetting ring and the connecting head, guard sleeve, and temperature compensator are bolted to the top wetting ring.

In an in situ test the probe is attached to a frame anchored to the ground, shown in Figure 3. The probe is pushed into a predrilled hole with a minimum of disturbance. Water is then introduced into the soil, and the subsequent swelling pressure developed against the probe is recorded. The instrument has been used at various levels in a clay profile, and the test results have been compared with the results of laboratory swelling tests performed on undisturbed clay specimens from the same site, using a modified oedometer ring (27). The remainder of this paper will concentrate on reporting further measurements made with these two instruments, which have been fully described in earlier papers.

SWELLING TESTS AT ONDERSTEPSPOORT

The soil profile in Onderstepoort (39) consists of a 3 m-deep residual clay of norite gabbro origin underlain by parent rock. The dominant mineral of the clay is smectite with some traces of kaolinite.



LEGEND

1. Ground frame
2. Water reservoir
3. Ground anchor
4. Drilling rod
5. Strain indicator

FIGURE 3 Field test using the in situ soil pressure probe.

Calcite and calcrite nodules are found in the profile. The clay has a liquid limit ranging from 79 to 99 percent, a plasticity index from 39 to 49 percent, and a clay fraction from 40 to 45 percent. Its linear shrinkage is about 20 percent. In profile the soil is stiff, fissured to shattered, and slickensided.

A series of laboratory and in situ swelling tests using the laboratory ring and the in situ probe was performed on the Onderstepoort clay. Remolded clay was tested in the laboratory in an attempt to simulate known site conditions and to compare the in situ swelling characteristic of an undisturbed clay and a controlled fill using the same material. Also, because the swelling characteristic is sensitive to sampling and test disturbance (39), laboratory swelling tests performed on remolded clay provide a wider range of possible results that can then be correlated to various field conditions.

Time-lateral pressure relationships for a series of in situ and laboratory tests are shown in Figure 4. In an in situ test, the introduction of water to the soil results in a decrease in lateral pressure, which occurs 30 to 60 min after water is introduced. The increase in the lateral pressure is associated with a decrease in the rate of flow of water into the soil, due to the low permeability of the saturated swelling clay around the probe.

The shape of the in situ time-lateral pressure relationship curve has a characteristic that is similar to the pressure-deformation relationship obtained in a cavity expansion test, for example, a pressuremeter test. The similarity can be explained by the fact that only the soil near the probe saturates, softens, and swells; the soil farther away from the probe does not suffer any significant change in its water content during the test and it acts as a stiff confining media (39). The in situ shear strength of the wet material determined after a test is in the range of 25 to 50 kPa, which provides further support to the statement explaining the lateral pressure determined in situ. The shallow test (Test 1 in Figure 4) was performed in a heavily desiccated section of the soil profile, and the introduction of water to the clay reduced the suction to zero and, consequently, a high lateral pres-

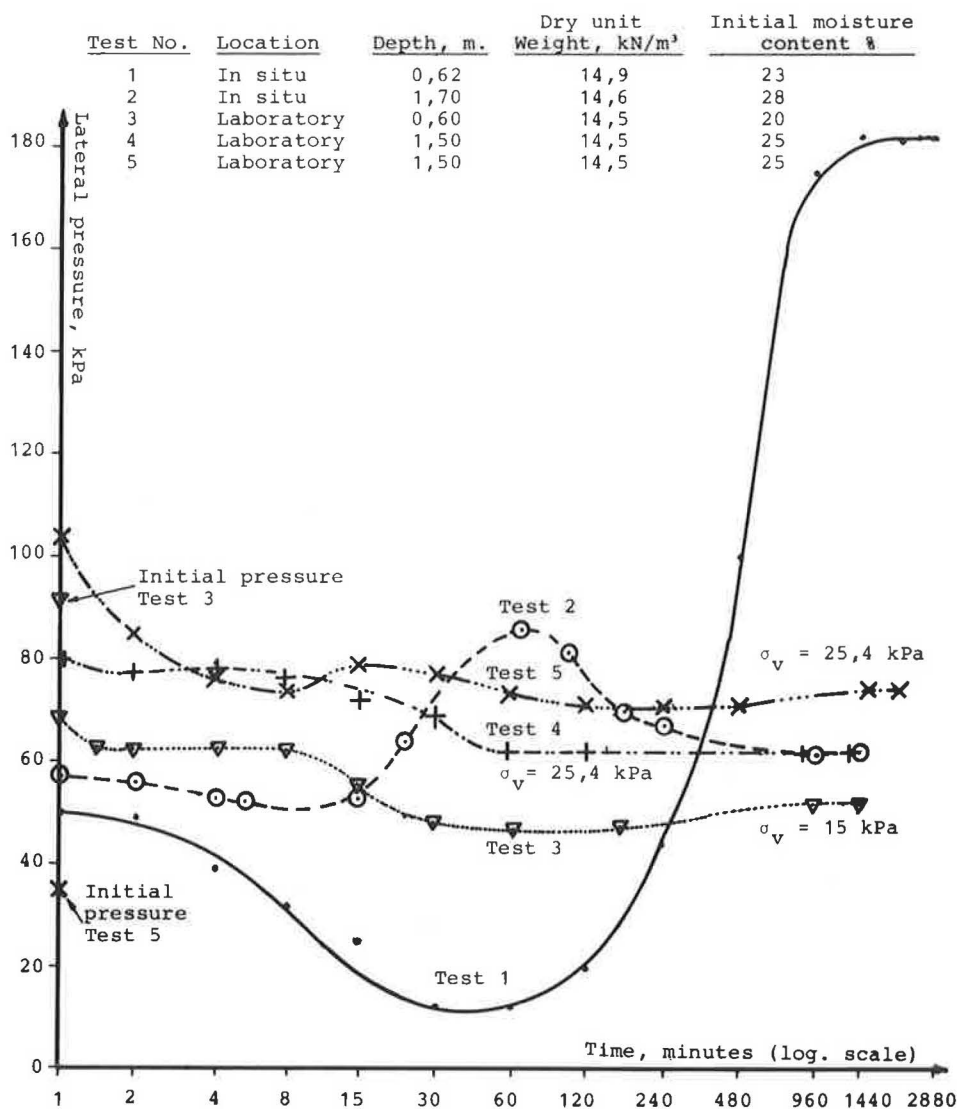


FIGURE 4 Time-lateral pressure relationship for swelling tests at Onderstepoort.

sure developed. The test was carried out at the end of the dry season when the clay is desiccated and the suction values are very high (pF 4,8). The lateral pressure recorded in this test represents the swelling pressure developed in the clay layer, near the probe, where it is confined by stiff clay that did not absorb the water supplied from the instrument. In the deeper in situ test (Test 2), the soil had both a lower density and a lower suction (pF 3,8), which explains the lower lateral pressure developed during the swelling test.

The laboratory tests were performed on statically compacted clay specimens. Subsequent to flooding, a decrease in the lateral pressure was observed in Tests 3 and 4; however, in Test 5, an immediate sharp increase in the lateral pressure was observed, followed by a subsequent decrease. The explanation for this anomaly in Test 5 is that at placement moisture content, the clay is in a granulated form and air voids exist between the specimen and the ring. Subsequently, some evaporation, drying, and shrinkage occurred, and the lateral pressure recorded initially in Test 5 before water was introduced to the sample was considerably lower than the initial lateral pressure recorded in Tests 3 and 4.

In all the tests an irregularity in the time-lateral pressure relationship was noted when water

was introduced to the top of the sample and 15 min after it was introduced to the bottom of the sample. One hour after the specimen was flooded, the lateral pressure readings stabilized. However, the clay was still absorbing water and further volume increases were observed.

Good agreement was found between the deeper in situ test (Test 2) and the corresponding laboratory tests (Tests 4 and 5) in which the final lateral swelling pressure was similar. The lateral pressure determined in situ 24 hr after water was introduced was 61 kPa, and the lateral swelling pressures determined in the laboratory in Tests 4 and 5 were 62 kPa and 74, respectively. It is concluded that the remolded clay tested in the laboratory performed similarly to the in situ clay. However, the in situ conditions of very shallow layers were not reproduced adequately in the laboratory.

An analysis of the in situ test results using plane strain constitutive equations for soils (28) relating the lateral-to-vertical effective stress ratio and the overconsolidation ratio provided unreasonable results. The overconsolidation ratio of the in situ clay is approximately 20 at a depth of 0.6 m and decreases to approximately 18 at a depth of 1.7 m. Using Hardin's equations, the corresponding effective angle of friction $\phi' = 90^\circ$, or al-

ternatively, if $\phi' = 20^\circ$ (reasonable value) the overconsolidation ratio, $OCR = 30,500$. The reason for this is that the in situ swelling test is in fact a cavity expansion test in which a layer of clay next to the probe expands and compresses the soil around it and the pressure monitored by the probe indicates the resistance of the partly saturated clay to compression.

TESTS AT LETHABO

The Lethabo site is underlain by horizontally bedded sedimentary rock of the Ecca subgroup, which is a part of the Karoo supergroup, overlain by layers of transported and residual soils. Residual soils are mainly weathered siltstones and occur as stiff to very stiff, fissured and shattered clayey silts. The residual siltstone grades with depth to very soft rock. Mineralogical analysis of the residual soil and siltstone indicated that about 30 percent of the silt-sized particles are quartz and the remainder is fine-grained micaceous clay. X-ray diffraction of the clay fraction shows that the dominant clay minerals are smectite and kaolinite with a small amount of illite.

In situ swelling tests on large-diameter, instrumented, bored cast in situ piles were performed during an investigation of piled foundations for a power station (11-35). The piles were 1050 mm in diameter, 33 m long, and were instrumented by means of vibrating wire gauges and electrical resistance strain gauges mounted in a central steel shaft. Three of a group of seven piles were instrumented. A month after the piles were constructed, water was introduced to the soil through a grid of watering holes, and subsequent soil heave and strain in the piles were recorded. In addition, a series of plugs 1050 mm in diameter and 2 m long was constructed at various depths in the clay. After wetting the soil in the manner described earlier, the pullout force-displacement relationship was recorded and hence the in situ shear strength of the soil determined.

Results of the in situ tests on instrumented piles and pullout plugs at the Lethabo site (11,35) and results of laboratory tests conducted on undisturbed siltstone specimens cut out from block samples from the same site are shown in Figures 5 and 6. Two types of laboratory swelling tests were carried out, for example, constant volume swelling pressure tests and heave under constant load tests. In both series of tests the siltstone specimens were initially placed in the oedometer ring for a period of 24 hr under a vertical pressure equal to the total in situ overburden pressure. The samples were then inundated and the swelling pressures or heave developed subsequent to flooding were recorded.

Lateral swelling pressures inferred from the plug pullout tests are considerably lower than the corresponding lateral swelling pressures determined in the laboratory. The reasons for this discrepancy are related to scale effects and selectivity in soil sampling. Intact specimens were tested in the laboratory, hence the swelling characteristic so determined yields conservative values, and it should be anticipated that in situ test results will be lower. In addition, the residual siltstone in the soil profile was fissured and shattered at the top of the soil profile and roots were observed down to 15 m, which allows a high apparent lateral compressibility. Hence the lateral swelling pressure developed in situ should be lower than the lateral swelling pressure recorded in a laboratory test on an unfissured specimen.

The relationship between the horizontal and vertical stress and the depth for the in situ tests and the laboratory tests is shown in Figure 5. It can be seen that from a depth of 4 to 10 m the lateral pressure inferred from the plug pullout tests is almost equal to the total vertical pressure in the profile. However, it can be seen in Figure 6 that the in situ lateral-to-vertical stress ratio K increases with increasing depth. In the laboratory tests, very high lateral swelling pressure was recorded in samples taken from a depth of 6 and 9 m, and the stress ratio K determined in these tests was

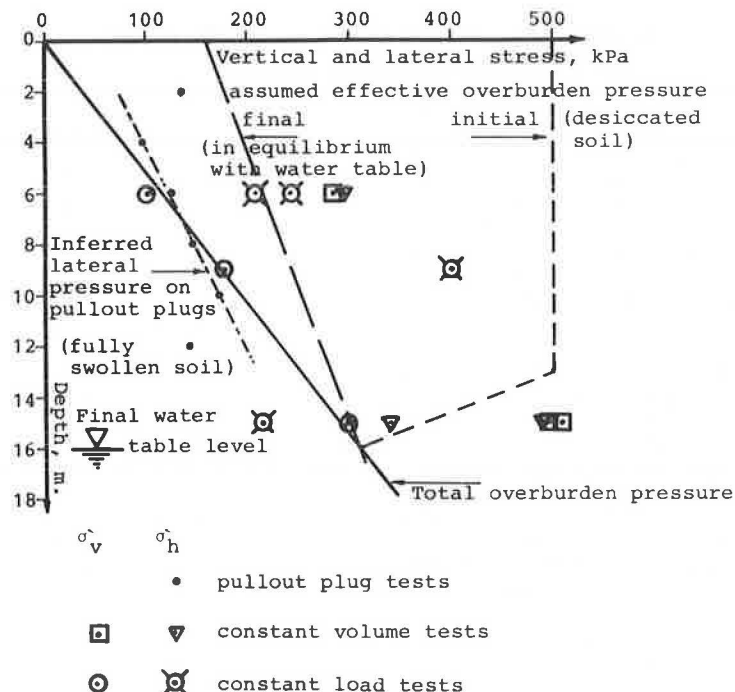


FIGURE 5 Vertical and lateral stress-depth relationship for tests at Lethabo.

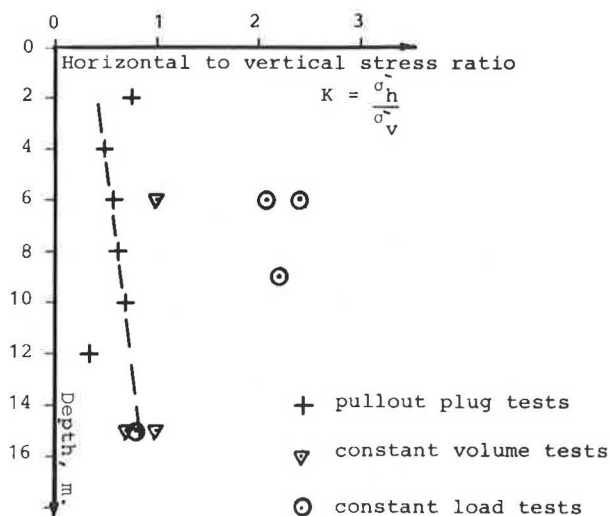


FIGURE 6 Stress ratio-depth relationship for tests at Lethabo.

considerably higher than 1. In samples taken at a depth of 15 m, the stress ratio K was approximately 1.

The scatter of the laboratory test results was high as a result of the sensitivity of the laboratory instrument to varying lack of fit of the specimens, the selectivity in soil sampling from the block samples, and possible drying of the samples between sampling and testing. However, it can be observed that both constant volume tests and constant load tests under a high overburden pressure gave stress ratio values that were in fair agreement with the values determined in the field tests. The initial total vertical stress was approximately the assumed initial in situ effective overburden pressure (shown in Figure 5); hence, the results show no effect of sampling disturbance and the simulation of true field conditions in the laboratory was good.

CONCLUSIONS

Some commonly used laboratory and in situ methods for the determination and prediction of swelling pressure and heave have been reviewed. Two instruments developed in South Africa have been described, and results of tests using these instruments have been presented and compared with field swelling and shear test results.

The effect of sampling and reproducing true in situ conditions in a laboratory swelling test on the laboratory test results is demonstrated. The selectivity in soil sampling and the small size of the laboratory specimens result in an overprediction of swelling pressure.

The laboratory instrument and the testing technique are very sensitive to specimen variability; therefore, an extensive laboratory testing program is necessary to obtain an improved relationship between laboratory and in situ test results. It is important to note that once true field conditions are well simulated in the laboratory and the effects of sampling disturbance and sample size are eliminated, the laboratory and in situ test results are in reasonably good agreement.

Results of laboratory tests on clay from Onderstepoort and the in situ test were in fair agreement; hence, it is concluded that it is possible to perform swelling tests on remolded clay in the laboratory and obtain valid and useful results correlating well to in situ swelling tests on soil at

similar water contents. The swelling pressures recorded in an in situ test represent the swelling pressure developed in a limited annulus of clay around the probe, confined by a mass of stiff drier clay. It will be necessary to conduct a swelling test over a long time period that will allow saturation of the clay farther away from the probe before this effect can be eliminated.

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