In Situ Stress Determination by Iowa Stepped Blade

By Richard L. Handy,[1] M. ASCE, Bernard Remmes,[2] Steven Moldt,[3] Alan J. Lutenegger,[4] and Gary Trott,[5] Associate Members, ASCE

Abstract: Lateral soil pressure is a vital element in soil mechanics theory and practice, but is very sensitive to disturbance and, therefore, difficult to measure. A step-tapered blade was developed to compensate for disturbance by measuring soil pressures on three thicknesses of blades, and extrapolating for the hypothetical pressure at zero blade thickness. The nature of the extrapolation was found to be exponential, with the slope theoretically inverse to the soil compression index C_c. In situ soil stresses measured in fine-grained soils generally agree with stresses from overburden pressures, elastic theory, and pressuremeters. Measured K_o's in natural soil deposits are generally within acceptable ranges, 0.5–1.5 depending on the consolidation state of the soil, and up to 4.2 in expansive clay. About 8–10 tests may be performed per hour; the test may not be reliable in dense sands. Directional horizontal stresses may be obtained with a three-bladed stepped vane.

Introduction

In situ soil stress is like an unruly emotion: It is invisible and impetuous, and wields a portentious influence on soil behavior. Lateral in situ stress is of obvious relevance for design of friction piles, underground structures, and retaining walls. In addition, it is fundamental to bearing capacity of shallow foundations, since the soil support underneath a foundation derives mainly from lateral restraint by soil alongside. Lateral in situ stress also should have a major influence on settlement, as in the analysis by Harr (5).

Lateral soil pressure, thus, plays a key role in engineering analysis and also in predictive modelling, as by the stress path and finite element methods. It is unfortunate that in situ lateral soil pressure, whether passive and developed by lateral squeezing, or inherited from its geological past, is at once a most difficult soil stress to predict analytically and to measure. Measurement of stresses within a soil mass poses the classic mensuration dilemma, that of the measuring tool

[1]Prof. of Civ. Engrg., Iowa State Univ., Ames, Iowa, 50011.
[2]Geotechnical Engr., McClelland Engrg., Houston, Tex.
[3]Geotechnical Engr., Warzyn Engrg., Inc., Madison, Wisc.
[4]Pres., Geotechnical Test Systems, Inc., Ames, Iowa 50010.
[5]Geotechnical Engr., Weidman & Singleton, Atlanta, Ga.

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altering what is being measured. One must either attempt to minimize the amount of change, or regulate it and correct for its effects.

Current Minimum-Disturbance Methods for Measuring In Situ

Horizontal Stress.—Hydraulic fracturing, Fig. 1(*a*), gives a measure of in situ stress in rocks or cohesive soils. Water pressure is increased through a drill pipe until the soil or rock fractures, indicated by a sharp increase in flow rate; pressure is then reduced until flow rate drops, indicative of the fractures closing, and giving a measure of in situ stress. Unfortunately, the direction of fracturing is determined by the direction of least tensile strength in combination with both the minor and intermediate principal stresses (3). Thus, the actual direction of the stress being measured may be a matter for conjecture.

Soil disturbance from hydraulic fracturing has been presumed to be minimal, but in tests in soft clays, Tavenas, et al. (19) found that about 50–100 days were needed for stress measurements to stabilize (Fig. 2). Agreement between hydraulic fracturing data and stress data obtained by other means has been reported as poor (19).

The Menard pressuremeter (Fig. 1(*b*)) avoids the uncertainties of fluid penetration and fracture orientation by keeping pressure expansion essentially inside a rubber bag confined axially in the borehole. Horizontal in situ stress has been

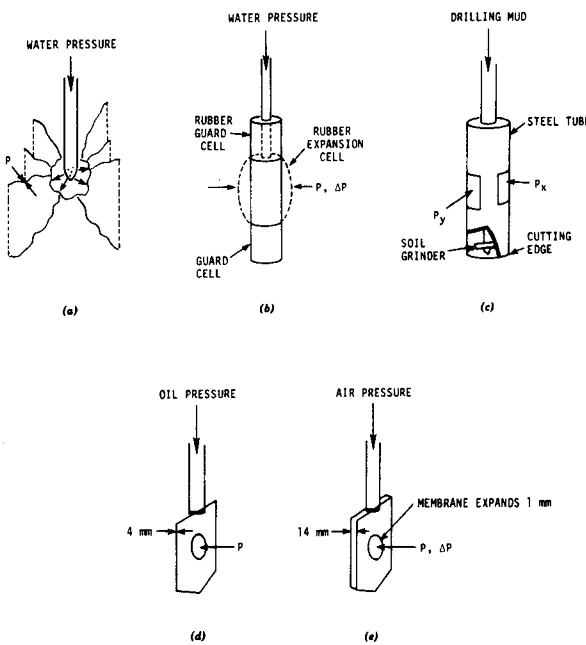

FIG. 1.—Current Methods for Measuring Horizontal Soil Stress In Situ: (*a*) Hydraulic Fracturing; (*b*) Menard Pressuremeter; (*c*) Self-Boring Pressuremeter (Camkometer); (*d*) Glotzl Cell; (*e*) Dilatometer

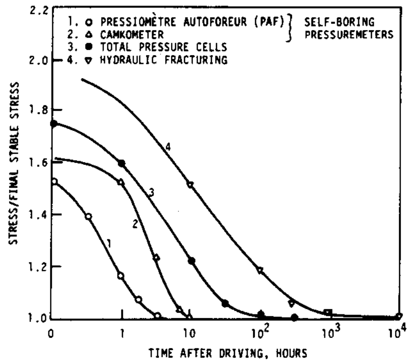

FIG. 2.—Stress Relaxation Times for Various Techniques of In Situ Horizontal Stress Measurement (from Tavenas (18))

inferred from changes in the pressure versus volume curve, but other uncertainties are introduced, particularly the influences of soil disturbance and imperfect fit of the pressuremeter in the drill hole (18). In France, where the pressuremeter is most widely used, measurement of lateral soil pressure by the pressuremeter for the most part has been abandoned, and lateral pressure is estimated for use in analysis (1).

Self-boring pressuremeters (Fig. 1(*c*) minimize the opportunity for relaxation of soil stresses in the vicinity of an open borehole by making the pressure measurement device integral with a rigid cylindrical cutter sharpened at the lower end by an interior bevel. As the cutter is pushed, soil inside is pulverzied by a rotating pug mill and is removed. The amount of disturbance is inferred by monitoring stress changes with time.

Gloëtzl total stress cells (Fig. 1(*d*), are thin, blade-shaped devices pushed into the soil and causing an appreciable over-stress that is monitored with time. As might be expected, the relaxation times required are 10–100 times those for the self-boring pressuremeters, and are measured in days or weeks (Fig. 2). The amount of overstress is minimized by making the cell thin, about 5/32 in. (4 mm) thick.

The Marchetti dilatometer (Fig. 1(*e*) is a flat stress cell that incorporates an expandable steel membrane in order to gain a measure of the soil response; to compression (9). The blade is relatively thick, 9/16 in. (14 mm). This gives a considerable overstress that has been evaluated from empirical comparisons to range from 3.7–8 on an effective stress basis.

The reduction of stress with time (Fig. 2) is a positive indication of disturbance from insertion of devices into soil. On the other hand, an absence of change with time does not necessarily signify the absence of initial disturbance, since overstresses may remain "locked in" in soils, such as sands and stiff clays with a relatively low susceptibility to creep.

Extrapolation Principle of the Stepped Blade.—Our goal was to devise an instrument to measure lateral in situ soil stress accurately at any desired depth without waiting for stress relaxation. It was concluded that for practical purposes

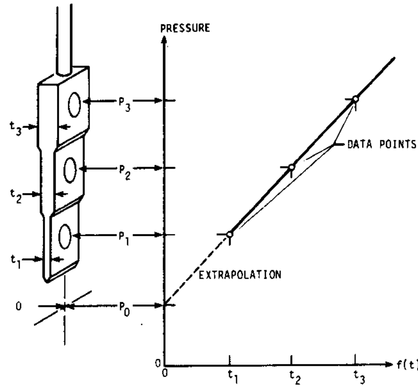

FIG. 3.—Schematic Diagram Showing Extrapolation Principle of the Stepped Blade

maintaining zero soil stress disturbance is impossible, and a less wearing alternative would be to introduce known levels of disturbance, establish a relationship between measured stress and disturbance, and extrapolate to zero disturbance. Although disturbance cannot be directly evaluated, it should relate to thickness of a penetrating blade. If so, by measuring pressures on several thicknesses of blades, one might extrapolate the pressure versus thickness relationship to zero blade thickness and evaluate in situ stress prior to insertion of a blade. This principle of the stepped blade is outlined in Fig. 3. The geometry of the stepped blade also was independently suggested by Marchetti (8).

It will be seen that the extrapolation does not literally mean no blade: It represents a planar discontinuity of zero thickness, meaning that the soil grains still conceptually must be moved out of the way. The extrapolated stress, thus, may be overestimated, the error being largest for dense, coarse sands whose dilation must be accommodated by volume changes in the surrounding soil. Thus, a similar extrapolation by La Rochelle, et al. (7) for vane shear tests with different blade thicknesses did not reproduce the correct undisturbed strengths.

Exploratory Tests.—Initial exploratory tests were conducted by pushing blades of different thicknesses into compacted 4 in. × 4 in. (102 mm × 102 mm) cylindrical soil specimens confined in an expandable split steel K-Test mold, to simulate lateral confinement by an ideally elastic soil (4). A schematic of the mold is shown in the inset in Fig. 4. The mold modulus is 15,900 psi (11 MPa), similar to a very stiff soil. A Teflon plate was clamped to the top of the mold to prevent vertical soil expansion; this plate was slotted for insertion of the blade (14).

Zone of Disturbance.—Color-layered soil specimens held in the K-test mold were penetrated by 2-in. (51-mm) wide blades having 60° apical wedge angles and various thicknesses and surface finishes. Each soil sample was removed, split, measured, and photographed to show thicknesses of the disturbed zones. Sand specimens were made with 1% portland cement, molded and tested dry, and then wetted and cured for one day prior to splitting. Clay specimens were made with oil-base modelling clay.

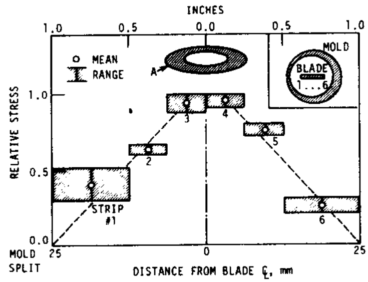

FIG. 4.—Stress Distribution across a 3.17-mm (1/8-in.) Blade Pushed into Soil in a K-Test Mold; Inset at Upper Right Shows Geometry of the Test; "A" Shows the Position of the Pneumatic Pressure Sensor Sealing Ring

Disturbed zone thicknesses were linear with blade thickness, and did not extrapolate to zero disturbance at zero blade thickness (14). The intercept value was found to be largest for a rough blade pushed into dense sand, less for a loose sand, and less for a smooth blade in loose sand or for blades pushed into clay, where blade roughness had no measurable effect on the disturbance zone. A smooth blade, thus, appeared advantageous for granular soils and was adopted.

Stress Distribution and Limit Pressure.—The distribution of stress across a blade face was determined by laying six parallel stainless steel strips 0.005 in. (0.13 mm) thick on one face to run the length of the blade, covering them with a brass sheet attached to the leading edge of the blade. After pushing the blade into 40% D_r sand contained in the K-Test mold, the total friction on each strip was determined from the pulling force required to initiate slip. The test was repeated with the pulling sequence reversed, and gave the ranges shown in Fig. 4. The stess distribution appears to be roughly triangular across the face of the blade, stresses being highest near the middle. A similar, parabolic distribution of pressure in sands was made by Koegler and Scheidig, quoted in Harr (5). Tests also were performed in sand held under constant load in a box, and stresses were more uniform but still highest in the middle. Subsequently, the stress sensor was designed to measure central stresses at approximately ±0.25 in. (6 mm) from the blade center line, as shown by ring A in Fig. 4. The variation in stress across the blade also suggests that blades should be uniform in width for a valid extrapolation from different thicknesses.

Later, it was found that insertion of thick blades into soft soils sometimes gives the same pressure regardless of blade thickness. From the pressure distribution of Fig. 4, one would expect more consolidation of soil in contact with the blade central portion than near the edges, particularly with the step-wise loading procedure of the stepped blade. This would build up a harder core of soil along the center line of the blade, and effect a transition from a flat loaded area to a triangular or elliptical one, in turn, leading to a limit pressure as obtained with the pressuremeter (1). Therefore, thin sequence of blades should be preferable.

Increase in Mold Stress from Soil Penetration by Blades.—Prior to development of a stress sensor, the K-Test mold was used to monitor lateral increases in average soil pressure resulting from blade insertion. As a check, the force to pull the blade was monitored and converted to blade stress by use of the soil-steel friction coefficient. Mold stress data were more reproducible and were best described by an exponential relationship:

$$p_1 = p_o a e^{bt} \qquad (1)$$

p_o and p_1 are, respectively, the initial and final lateral mold stresses; t is the blade thickness; and a and b = regression coefficients. Correlation coefficients r for Eq. 1 ranged from 0.964–0.999, averaging 0.990 from nine tests. Representative data from smooth blades are shown in Table 1.

The regressions of Table 1 are based on mold stresses, which must underestimate central stresses on the blades and, therefore, underestimate a. The a coefficient is significantly higher for dense sand than for the other soils, and also was found to be higher for rough blades compared to smooth blades in sand (14). As will be shown later, the ideal value for a is 1.0. The b coefficient represents a stiffness response to blade intrusion, and was essentially constant, indicative of the modulus of the steel mold. As shown in Table 1, the exponential fit also held true for narrower blades, and the b coefficient is reduced because of the smaller volume displacement. Comparative tests with blade wedge angles of 45°, 60°, and 90° showed the 60° angle resulted in lower a coefficients, so this angle was adopted (14).

A moderate penetration rate, 0.65 in./min (0.275 mm/s) was found to be best for the oil-base modelling clay (14). In the field version, pushing is stopped and the load of drill rod lifted from the blade by means of a slip joint prior to taking readings to avoid measuring increases in stress due to blade-soil friction.

A series of 34 tests was conducted to evaluate the effects of time delays. Waiting five minutes allowed mold stresses to be reduced from 1–5%, the latter for the soft clay. After 15 minutes, stresses were lower by 5–11%, the least

TABLE 1.—Exponential Fit of Eq. 1 to Mold Stresses after Penetration of Soils with Three Thicknesses of Blades

Soil (1)	Regression Coefficients: a (2)	Regression Coefficients: b, in millimeters^{-1} (3)	Correlation coefficient[a] (4)
2-in. (50-mm) blade			
40% D_r sand	0.7	10.7	0.999
75% D_r sand	2.6	10.5	0.997
Soft modeling clay	0.5	11.1	0.979
Stiff modeling clay	0.7	10.5	0.964
1-in. (25-mm) blade			
40% D_r sand	0.7	8.6	0.994
Soft modeling clay	0.7	5.2	0.999

[a]With three points (one degree of freedom), r = 0.999 is significant at the 97% confidence level, 0.997 at the 95% level, 0.998 at the 90% level, and 0.951 at the 80% level (17).

[b]D_r = relative density.

change being for dry Ottawa sand. Therefore, it was decided that time between pushing a blade and measuring the stress should be consistent, and preferably should be minimized to expedite testing.

Stress Sensor Tests

Sensor Design.—A pressure-balance pneumatic sensor was designed whereby soil pressure on one side of a diaphragm is opposed by regulated gas pressure on the other. Gas pressure is gradually increased until the diaphragm lifts away from a 0.5-in. (25-mm) diam sealing rim (Fig. 5), allowing gas to escape to an exhaust line that is monitored with a bubbling device or a flow gage. At the moment flow initiates, the actuating gas pressure is read to give blade stress in the central area. The pressure is than reduced and the procedure repeated two or three more times for precision and averaging. While any nontoxic gas or air may be used in the sensor, CO_2 was selected as a convenient liquified source of gas for field tests.

Brass, stainless steel, and Teflon were tested and evaluated as diaphragm materials, and 0.250-mm (0.010-in.) thick Teflon-TFE was finally selected for linearity of response, durability, and ease of replacement in the field. Calibrations were linear, with exceptionally good reproducibility, the gage pressure exactly equalling the soil pressure.

Small Box Text.—Blades with pneumatic stress sensors were pushed into standard Proctor-compacted loess soil held in a steel box 11 in. wide by 36 in. long by 6 in. deep (279 mm × 914 mm × 152 mm) with a movable lid that was dead-loaded by use of a loading yoke and a platform scale. A hole at one end of the box allowed horizontal insertion of the blades, which were pushed and withdrawn sequentially from the thinnest to the thickest. The data fit the exponential form of Eq. 1 with a = 1.17, b = 3.76 mm^{-1}, and r = 0.991. This was the first confirmation of the exponential nature of the relationship outside of the K-test mold. Also, the relatively softer boundary conditions gave a = 1.17, close to, but still larger than, 1.0.

Prediction Equation.—Eq. 1 rearranged for the initial in situ stress is $p_o = 1/a\ p_1 e^{-bt}$. If a is assumed tentatively to be 1.0

$$p_o = p_1 e^{-bt} \qquad (2)$$

With use of Eq. 2, a value of a other than 1.0 will become manifest as error in the determination of p_o.

Large Box Test.—A densely compacted SC clayey sand soil contained in a 10-ft (3-m) square concrete box at the Federal Highway Administration Langley Research Station, McLean, Virginia, was tested with the single stepped blade. The soil had been compacted previously to 100% standard Proctor density and used for pavement subgrade loading studies, and represents an extreme firmness condition and resistance to blade penetration. Pressure readings indicated that a limit pressure was reached with the thickest (1/4 in., 6 mm) blade, so an exponential relationship could not be confirmed. An exponential fit of Eq. 2 to the first two points gave b = 0.44 mm^{-1}, which is high and indicative of a stiff soil. Extrapolation to zero blade thickness gave p_o = 11.4 psi (78 kPa), but, unfortunately, no other comparative stress data are available. The test depth of

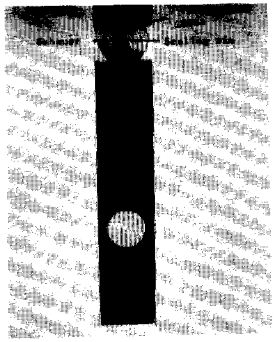

FIG. 5.—First Two Steps of the Stepped Blade: (Top) Disassembled to Show Pneumatic Pressure Cell, and (Bottom) Assembled with the Teflon Diaphragm Held in Place by a Press-Fit Retainer Ring

2.5 ft (0.70 m) give a calculated overburden pressure of 2.2 psi (15.2 kPa), and $K_o = 11.4 \div 2.2 = 5.1$, as may be expected at shallow depth in a heavily overconsolidated soil.

Field Tests

The costs of compacting soils in large boxes with still unknown boundary effects, led to the alternative of measuring soil horizontal and overburden pressures in the field. Field trials used three generations of blades: three separate 2-in. (51-mm) wide blades; the single sequentially stepped blade shown in Fig. 5; and a 4-in. (102-mm) diam, step-bladed vane with blades spaced at 120° for simultaneous evaluation of directional horizontal stresses. All data were reduced with Eq. 2.

Overburden Pressures and K_o

Overconsolidated Loess.—The first field in situ test was conducted in soil exposed in a roadcut southwest of Boone, Iowa. From the top down, the cut penetrates 38 ft (11.5 m) of Wisconsin-age glacial till, 8 ft (2.4 m) of loess, and a pre-Wisconsin till. The loess, being thin and having been overriden by a continental glacier, was expected to be overconsolidated. The soil was unsaturated, its natural moisture content being slightly below the plastic limit. The single blades were pushed horizontally in both vertical and horizontal orientations. Data and coefficients of Eq. 2 are shown in Fig. 6(*a*). A limit pressure was reached on the thickest blade, so that only the first two blade stresses were used in exponential data fits. Elastic analysis assuming homogeneous soil in the cut gives a vertical stress of about 16 psi (110 kPa) or 5% higher than that which was measured. $K_o = 1.3$, indicative of an overconsolidated soil. This may be the first direct measure of both components of K_o to be made in the field.

Underconsolidated Loess.—Underconsolidated, low-clay-content loess was tested with single blades in a steep, 35-ft (11.5-m) deep roadcut near Turin in western Iowa. The moisture content was low, and the moist bulk density is about

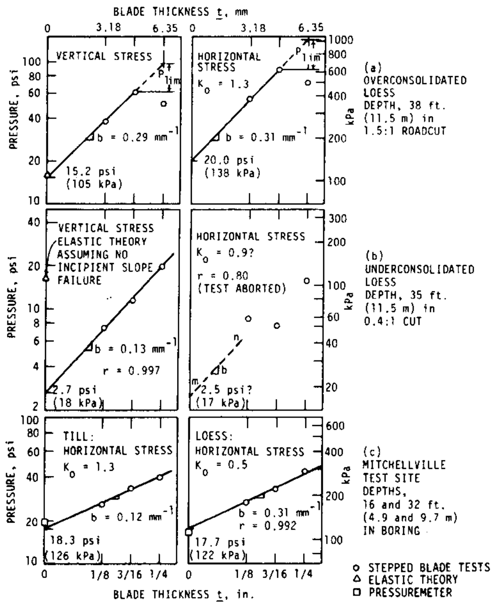

FIG. 6.—Exponential Fits of Eq. 2 to Field Test Data, and Comparable Vertical Stress Data from Other Sources

100 pcf (1.60 g/cm^3). The tests were conducted at the end of a 10-ft (3-m) deep hole bored horizontally from the face, and both horizontal and vertical stresses were measured. Results are shown in Fig. 6(*b*). This was the first field confirmation of an exponential relationship, r for the vertical test being 0.997, but the measured vertical stress is only about one-sixth of that indicated by elastic analysis assuming homogeneous soil conditions. This may relate to incipient failure of the lower soil in unconfined compression following vertical trimming of the lower 5-ft (1.5-m) of the cut by a blade grader. No other comparative in situ stress data are available, so it is not known if this test is valid. The horizontal test data are erratic and r is low, which may relate to stress relief near the cut face, often manifest as slab spalling. Even though r is low and the test is aborted, some information may be salvaged by using the b slope data from other tests in the same soil and extrapolating as shown by line mn in Fig. 6(*b*).

Stepped Blade versus Pressuremeter Horizontal Stress Data.—A late Wisconsin-age glacial till end moraine and the underlying Early Wisconsin loess near Mitchellville in central Iowa were tested with the single stepped blade, and with the Menard pressuremeter (2,11). Plots of the data and the Eq. 2 regressions are shown in Fig. 6(*c*). The close agreement between pressuremeter and blade p_o data was welcomed, if not anticipated.

Effective stresses prior to blade insertion were calculated by subtracting static pore water pressures; the water table was at a depth of 12 ft (3.7 m). The effective overburden pressures for the till and for the loess were calculated to be 12.9 psi and 19.5 psi (89 kPa and 134 kPa), respectively, giving K_o = 1.3 for the till and 0.5 for the loess. Thus, the glacial till appears to be overconsolidated by the weight of glacial ice, while the underlying loess was not. This phenomenon has been observed elsewhere and is a topic of current research.

Stepped Blade versus Self-Boring Pressuremeter Data.—The self-boring pressuremeter is perhaps the most accurate existing method for evaluating horizontal in situ soil stresses (1). Stepped blade tests were performed at 5 ft (1.5 m) depth intervals with the single stepped blade in expansive Beaumont clay at the University of Texas Houston Campus. Later, after the blade tests had been interpreted, self-boring pressuremeter results were made available. Blade tests were performed in two holes to 50-ft (15-m) depth to replicate data.

In this soil, stresses on the 1/4-in. (6.35-mm) blade were invariably lower than those with the next thinner blade and indicative of a limit pressure. Data from the thickest blade section were, therefore, not used, and the exponential relationship of Eq. 2 was fitted to pressures from the other two thicknesses.

In order to regain some statistical averaging effect, *b* values were regressed versus depth in each boring (Fig. 7). Several of the values appeared to be too high, probably caused by proximity to calcareous nodules in the clay. These were rejected and are shown by open points in the figure. Since the slope *b* has such a large influence on the extrapolated in situ stresses, normalized *b* values calculated from equations in Fig. 7 were used to calculate an in situ stress from each data point (Fig. 8). Tests were performed in duplicate at nearly the same depth in each boring, giving as many as eight stress readings at each depth. Of a total of 75 stress measurements that were made in about six hours (including drilling), seven were rejected on initial data reduction because of unrealistic *b* values, and 14 other points were rejected as outliers. One-third of the rejected data points were from one depth in one hole where running sand was encountered.

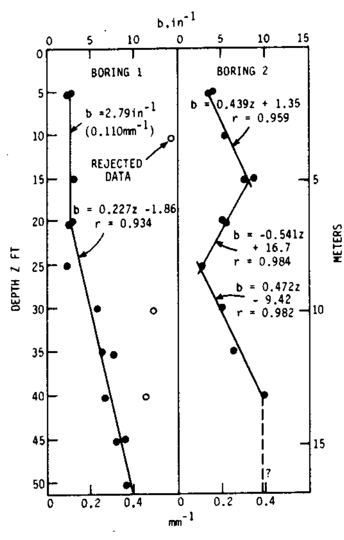

FIG. 7.—Houston Clay Stiffness Coefficient *b* versus Depth; 1 in.$^{-1}$ = 0.03937 mm^{-1}; Equations are in English Units

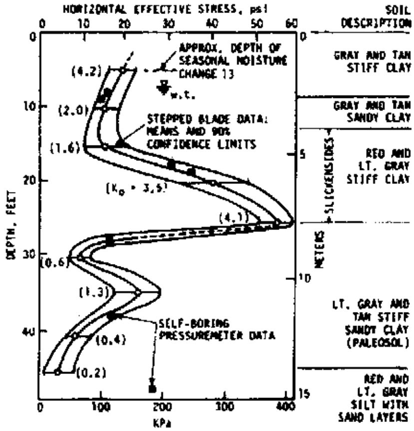

FIG. 8.—Horizontal in Situ Stresses Measured in the Beaumont Clay; Numbers in Parentheses are K_o's from Blade Stress and Soil Unit Weights; Pressuremeter Data are Courtesy of Fugro-Gulf, Inc., and Federal Highway Administration

Horizontal effective stresses obtained by subtracting the static pore water pressures versus depth are shown in Fig. 8. The peak stress occurred in a zone described in the boring log as having slickensides, or inclined shear planes attributed to high horizontal expansive pressures causing shear failure of the soil. In this zone, K_o ranges from 1.5–4.2. A second peak stress occurred at a depth of about 35 ft (10.7 m). Since both peaks are below the water table, they support the concept that they may be relict stresses inherited from wet-dry cycling with crack filling from a previous lower ground surface prior to deposition of the overlying sediments, as suggested by O'Neill and Ghazzaly (12). Both peak stresses are below the depth of significant seasonal moisture change (13), but the soils at these depths show tan and red colors indicative of an earlier oxidizing environment. The high stress near the present ground surface presumably represents a current production of horizontal expansive stresses.

Of particular concern is the agreement between extrapolated p_o pressures from the blade and from the self-boring pressuremeter. Only at the lowest depth where the sand layer was encountered was there appreciable disagreement. The pressuremeter pressures were read to the nearest ±2.5 psi (17 kPa), and the average differences between the two methods was 1.7 psi (12 kPa). Two of the blade stresses were higher than pressuremeter values, three were lower, and one was the same. This agreement supports the use of the exponential data fit of Eq. 2 wherein a of Eq. 1 is assumed to be 1.0.

Stepped Blade Tests in Heterogeneous Residual Silt Soil.—Tests were conducted at nominal 5-ft (1.5-m) intervals in two borings in residual micaceous silt soil at the Federal Highway Administration Langley Research Station, McLean, Va. As at Houston, the thickest 1/4-in. (6.35-mm) blade section invariably caused limit pressures to be reached; so b values were obtained from data pairs. Since b's showed considerable scatter (Fig. 9(a)), they were regressed versus depth. The change in b with depth is significant only in Boring 1, at the

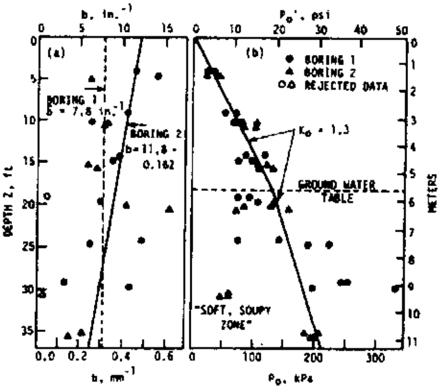

FIG. 9.—Langley Station, Va., Residual Soil Data: (a) *b* Values from Data Pairs; (b) Horizontal Effective Stress

80% confidence level. The soil contained erratic hard and soft zones from weathering along fractures, explaining the scattered *b* data. In situ stresses should not vary as much as the soil stiffness, and since *b* variability acts as a lever arm to increase intercept variability, normalized *b* values from averaging or from the regression versus depth were used to reduce blade stress data.

The results show a consistent increase in pressure with depth (Fig. 9(*b*)). Based on an assumed density and moisture content, K_o is about 1.3, presumably indicative of a soil preconsolidated through removal of overburden by geological erosion. However, the extrapolation to zero stress at zero depth does not appear to be consistent with this explanation. Other possibilities are that the high horizontal stress relates to hydration expansion of primary minerals on weathering, or that it is inherited from regional tectonic stresses present in the parent rock. Horizontal stresses appear more erratic below the ground water table, in the transition zone to rock.

The 45 tests at Langley, including two which were aborted, were performed in about five hours. Comparative tests with a self-boring pressuremeter were planned, but unfortunately no data are yet available.

Vane with Three Stepped Blades.—A design modification was made whereby three stepped blades were assembled together radially in the manner of a van shear, the blades being 120° from one another. This was done to provide a redundancy of data, and to reveal directional anisotropy in horizontal stress. The three-bladed vane was made with thinner blades to reduce the likelihood of encountering a limit pressure; the thickest blade was 3/16 in. (4.76 mm) compared to 1/4 in. (6.35 mm) for the single stepped blade. Other thicknesses on the vane are 5/32 in. and 1/8 in. (3.97 mm and 3.18 mm), while blade widths remained the same, 2 in. (51 mm).

Clay Paleosol and Squeezing Loess.—Tests of a shallow (10 ft (3 m) depth), very soft, saturated loess soil that would not hold an open hole reached very low limit pressures with the thinnest blade; so no interpretations were made of in situ stress. Underneath this soft layer was a firm, montmorillonitic paleo B horizon known as "gumbotil." Here limit pressures were not reached (Fig. 10(*a*)), and

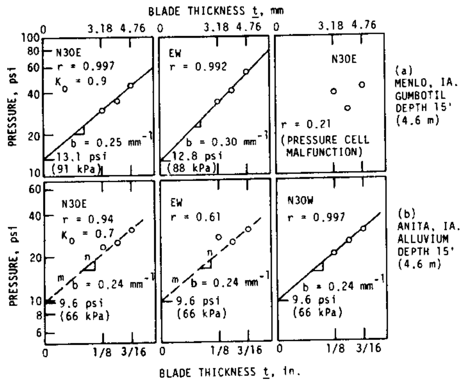

FIG. 10.—Horizontal Stress Tests with Triple Step-Bladed Vane

two of the blades gave high values for r, fairly close b values, and pressures within 3% of one another. The third blade gave low r and b values, and the data were rejected. The post-test recalibration of pressure cells revealed a plugged gas line in this blade. K_o at the test depth was 0.9, and presumably had been much higher prior to burial under the weight of the loess.

Alluvial Sand-Silt-Clay with Surcharge Load.—Tests were conducted with the three-bladed vane next to a grain elevator loaded to approx 1 ton/sq ft (96 kPa). Elastic solutions indicated that the horizontal pressure due to surcharge should peak out at a depth of about 15 ft (380 mm), where the influence coefficients are 0.30 radially and 0.25 tangentially, which gives a maximum directional stress variation of only 0.7 psi (5 kPa). The test data (Fig. 10(b)) gave two low r values, indicative of test error. If we reduce all data using $b = 0.24$ mm^{-1} from the one successful regression, seven of the nine extrapolated pressures are in the range 9.6–9.9 psi, with no measured anisotropy of horizontal stress.

Advantage/Disadvantage of the Vane over the Blade.—The main usefulness of the vane was to provide a redundancy of data. Stress anisotropy can be analyzed for principal stress directions by the equations for a rosette strain gage, or the single blade may be directionally oriented where anisotropy is suspected. The vane has greater rigidity, which will allow the use of thinner blades. The reduction in maximum blade thickness helps to avoid limit pressures, but magnifies sensitivity of the extrapolation because of the reduced range in t.

Theoretical Relationships

An exponential relationship between blade thickness and pressure was not anticipated, particularly in the early laboratory tests when the soil was confined in an expandable elastic steel mold. Nonlinear behavior is routinely observed with the pressuremeter as the pressure tends to attain a limit pressure (curve OCD in Fig. 11). According to elastic theory, expansion of a cylindrical cavity simultaneously increases the radial major principal stress and decreases the tan-

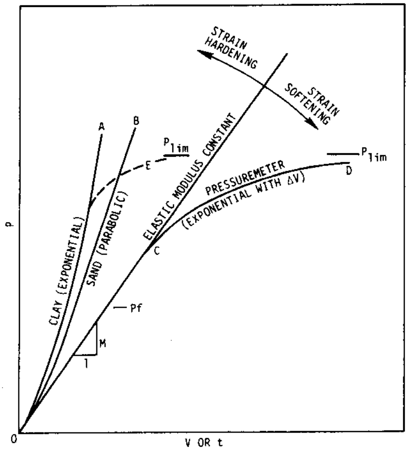

FIG. 11.—Theoretical and Observed Pressure-Volume Responses for Soils: OA is Consistent with Linear e log p Relationship

gential minor principal stress in soil around the cavity, both effects diminishing with distance outward. In the zone of maximum combined influence, there is shear failure and development of an annular plastic zone. The radial compressive stress to initiate failure, p_f, depends in part on the induced tangential tensile stress, and on the soil cohesion and angle of internal friction. The limit pressure $p_{\lim}$ depends on the factors affecting p_f and in addition on the strain to failure (1). The net effect, strain softening is, thus, attributed to radial expansion of the plastic zone.

The observed exponential relationship for the blades is opposite to that for the pressuremeter, and indicative of strain hardening rather than strain softening (curves OA and OB in Fig. 11). Janbu (6) suggested that for normally consolidating clays the compressive tangent modulus M is proportional to consolidating effective stress p':

$$M = \frac{dp'}{d\epsilon} = mp' \quad \text{(3)}$$

in which ϵ is unit strain, and m is a constant. Solving for ϵ gives

$$\epsilon = \int_{p'_o}^{p'_1} \frac{dp'}{M} = \frac{1}{m} \ln \frac{p'_1}{p'_o} \quad \text{(4)}$$

in which p'_o and p'_1 are initial and final consolidating pressures. Total settlement S is a summation of unit strains through depth H:

$$S = \frac{1}{m} \int_o^H \ln \frac{p'_1}{p'_o} dz \quad \text{(5)}$$

From elastic theory, it can be shown that the ratio of two applied stresses, p'_1/p'_o is constant, regardless of depth z relative to a surface load. Thus

$$S = \frac{H}{m} \ln \frac{p_1'}{p_o'} \qquad (6)$$

from which $p_o' = p_1' \, e^{-mS/H}$ (7)

in which H = the thickness of the consolidating layer. Settlement S may be substituted by blade thickness $t/2$. Thus

$$p_o' = p_1' \, e^{-mt/2H} \qquad (8)$$

From elastic theory, the effective thickness H of the consolidating soil continuum must represent a summation through the gradually dissipating pressure bulb, and relates to contact area dimensions, not to the amount of settlement, represented in this case by thickness of the blades. We, therefore, may assume that the effective H is constant for constant blade face dimensions, and define $b = m/2H$:

$$p_o' = p_1' \, e^{-bt} \qquad (9)$$

This is the same as the empirical Eq. 1, with $a = 1.0$.

The aforementioned development is consistent with the commonly observed linear relation between void ratio and logarithm of pressure, since as shown later, the compression index C_c is inverse to m (6). We may surmise, therefore, that an exponential fit is appropriate for blade data if all blade stresses are within a consolidating stress regime for which there is a linear e-log p relationship.

The above argument does not address the problem of excess pore pressure, which will reduce p_1' in Eq. 4. Eq. 9 may be restated

$$p_o' = (p_1 - u) \, e^{-bt} \qquad (10)$$

in which u is dissipating pore pressure after load p_1 is applied. Consolidation theory states that, for a soil mass of thickness H, the initial pore pressure equals the load increment, and the pore pressure dissipation is a function only of consolidating time. If u at a particular depth and time is proportional to p_1, the exponential relationship will be preserved, and p_o may be predicted regardless of the developed excess pore pressure. Pore pressures are not measured in the present blade devices, and are a goal or current research.

The coincidence of the blade stress data with one-dimensional consolidation suggests that a flat blade shape is preferable to a cylindrical probe. Furthermore, if the blade is thick, the centralized pressure distribution in Fig. 4 predicts that there should be the observed transition to cylindrical, pressuremeter-type behavior manifested by occurrence of a limit pressure, curve OAE in Fig. 11, so a thin blade appears preferable.

Blade versus Pressuremeter Limit Pressures.—Blade pressure readings often will bracket limit pressures; the limit pressure is higher than the highest reading and lower than the extrapolated pressure in the next thickest blade. This is shown by the two tests in Fig. 6(a), where both the in situ stress and the limit pressure probably are higher in the horizontal than in the vertical direction. Limit pressures were not reached in the Mitchellville tests, Fig. 6(c), where pressuremeter limit pressures all exceeded the maximum pressure on the blades (2). Limit pressures consistently were reached in the Houston clay tests, with ranges

TABLE 2.—Stepped Blade and Self-Boring Pressuremeter Limit Pressures, Houston Clay

Depth, in feet (1)	P_{lim}, in pounds per square inch: Pressuremeter (2)	Boring 1 (3)	Boring 2 (4)
8–10	60, 100		
18–20	115, 120	97–114	125–180
28–30	140	>82	49–66
38–40	>200	99–138	78–232
48–50	>200	80–160	>23

shown in Table 2. Pressuremeter limit pressures were estimated by extrapolating the pressure-radial strain curves. We may conclude that limit pressures from the two tests sometimes are closely comparable, or the blade limit pressure may be lower, as might be expected from the greater amount of soil compression and attendent positive pore pressures. It should be noted that the data are from three different borings, and the blade data show a considerable variation in limit pressures between different borings.

Significance of *b*.—In the development of Eq. 9, b was defined as $b = m/2H$, in which m = the modulus proportionality constant of Eq. 3, H = the thickness of the compressing soil layer adjacent to the blade. Janbu (6) shows that m relates to the compression index C_c by

$$C_c = (\ln 10)(1 + e_o)\frac{1}{m} = (1 + e_o)\frac{2.3}{m} \quad \text{(11)}$$

in which e_o is the initial void ratio. Substitution for b gives

$$C_c = \frac{1}{b}\cdot\frac{2.3(1 + e_o)}{H} \quad \text{(12)}$$

The second term should be constant for a given soil, H representing an equivalent thickness of the consolidating layer. Thus, $H/2$ may be seen as distance to the consolidation centroid of the pressure bulb. This, in turn, relates to both soil and geometric factors, and appears most appropriately evaluated by experimentation. This has not yet been done. Encouragement may be derived from the similar use of the dilatometer to derive a tangent modulus (9) that was later shown to agree with that from the odometer test within a factor of 2 (16).

Conclusions

1. Stress measurements made on several thicknesses of flat blades pushed in sequence into a soil in situ may be extrapolated to give a theoretical stress on a blade of zero thickness.
2. The in situ stresses thus obtained for the most part appear reasonable, and agree with stresses from overburden pressures and elastic theory or measured by use of the pressuremeter or self-boring pressuremeter.
3. The stepped blade method is applicable to fine-grained soils over a wide

range in firmness, except those with open cracks or voids. The blade cannot be pushed in dense sands.

4. The nature of the pressure:blade thickness relationship usually is exponential, of the form $p_o = ap_1e^{-bt}$ in which p_o = the prior in situ stress; a = a constant assumed to be 1.0; p_1 = the measured blade stress; t = the blade thickness, and b = a soil compressibility factor experimentally determined from stress measurements on two or more thicknesses of blades. The exponential relationship is explained by an increase in compression modulus with pressure, which is consistent with a linear relation between soil void ratio and logarithm of pressure during drained one-dimensional consolidation.

5. Too thick a blade causes a limit pressure to be reached, attributed to transition from a flat plate to a radial stress distribution analogous to that of a pressuremeter. This disrupts the exponential relationship. It is minimized by use of thin blades, with a thickness:width ratio of 0.10 or less, but may be unavoidable in very soft soils.

6. The sensitivity of the extrapolation to variations in the soil compressibility parameter b supports the use of normalized values of b obtained from regressions versus depth. Therefore, test repetitions are necessary for statistical confidence, particularly in variable soils. With repetitive tests, the measurement precision often is within ±1 psi (7 kPa).

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