

# Lateral Response and Earth Pressure Parameters of Cohesionless Soils Related to Flat Dilatometer Data: A Laboratory Study

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In situ evaluation of soil parameters in the lateral direction such as the at-rest lateral earth pressure coefficient, lateral subgrade coefficient, and lateral soil modulus is required for a variety of soil-structure interaction analyses. A practical device to estimate these parameters is the flat dilatometer. The flat dilatometer requires, however, as do most other in situ penetrometer-type devices, calibration under simulated in situ conditions for possible extrapolation of the results to undisturbed soil conditions. A series of laboratory experiments was conducted to investigate the effects of dilatometer penetration on the soil parameters estimated from the dilatometer data in sands. With regard to the at-rest lateral earth pressure coefficient, the results indicated that the relation between the in situ earth pressure and the lateral earth pressure measured after dilatometer penetration is a function of particle shape characteristics as well as relative density and vertical overburden pressure. The lateral subgrade coefficient and the lateral soil modulus were found to be reasonably linear functions of the corresponding soil parameters determined from the dilatometer data, namely the dilatometer subgrade reaction coefficient and the dilatometer modulus. The range of uncertainty, however, was found to increase with the angularity of the particles in soil. Both particle shape and relative density become controlling factors for the slope and the linearity of these relationships in soils composed of angular particles.

As a result of the rapidly increasing data base during recent years for a variety of in situ test devices involving a wide range of soil types and conditions, and improvements in the design of these devices, there is a growing confidence among geotechnical engineers in predicting soil properties by in situ test methods.

The flat dilatometer is capable of yielding data that can be related to various geotechnical parameters by means of a series of empirical correlations. Field data are obtained by penetrating a rectangular flat blade tapered at the tip into the soil and expanding a vertically mounted steel diaphragm on the blade against the soil. The diaphragm is expanded by introducing gas under pressure into the chamber behind it. Two readings are taken: (a) the pressure to start the outward movement of the

diaphragm ( $p_0$ ), as determined by the silencing of a continuous beeper tone on the control unit, and (b) the pressure necessary to displace the diaphragm center toward the soil by one millimeter ( $p_1$ ) as determined by reactivation of the beeper tone. Previous applications of the flat dilatometer include the profiling of subsurface soils in a nearly continuous manner and the estimation of a number of soil parameters such as the at-rest lateral earth pressure coefficient, the overconsolidation ratio, the coefficient of volume compressibility, and the liquefaction susceptibility of saturated fine sands. The flat dilatometer also promises to be a useful tool for assessing soil response against lateral loading for soil-structure interaction analyses.

The study described herein was conducted to relate the at-rest lateral earth pressure coefficient, the lateral subgrade coefficient, and the lateral soil modulus for sands of different grain shape characteristics to the dilatometer data obtained during a penetration test. The scope of work of this study is wider than that of a similar study reported elsewhere (1) in terms of materials used and improvements made to the laboratory and to the test methodology.

## LABORATORY STUDY

The experimental work was conducted in a steel bin under controlled relative density and simulated overburden pressure using three sands of different particle shape characteristics and somewhat different grain size distributions. The grain size distribution in all three sands can, however, be characterized as uniform. Figure 1 shows an overall view of the laboratory setup. The improvements made to the original equipment described elsewhere (1) include the enlargement of the pressure plate to distribute the load over the entire surface area of the specimen and the insertion of a "face" plate to improve the initial lateral stress conditions. The at-rest pressure and the at-rest condition dilatometer modulus were obtained by using a dilatometer diaphragm mounted on a rectangular aluminum block as shown in Figure 1.

To obtain the pressure-diaphragm deflection curve in a continuous form, a leaf-type cantilever beam deflection sensor, instrumented with a half-bridge strain gauge arrangement, was used behind the diaphragm. A steel pipe section was attached to the back of the aluminum block and was extended out through a hole on the short side of the bin and the face plate. To

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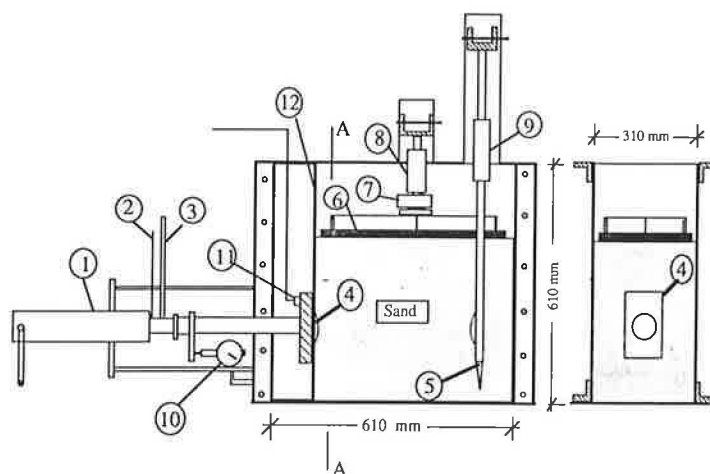


FIGURE 1 Experimental setup for penetration testing: 1. trailer jack, 2. deflection sensor leads, 3. pressurized nitrogen line, 4. aluminum block, 5. flat dilatometer, 6. pressure plate, 7. load cell, 8. and 9. hydraulic jacks, 10. dial gauge, 11. pressure transducer, 12. aluminum rectangular block.

simulate the lateral separation of the soil during dilatometer penetration, the aluminum block was laterally forced into the soil using a trailer jack mounted rigidly on a steel frame that, in turn, was welded to the short side of the bin. Overburden pressure was simulated by applying a vertical force through a hydraulic jack on a rigid steel plate placed on the surface of the soil specimen. The vertical force was measured by a load cell mounted between the steel plate and the hydraulic jack. During the tests, a standard dilatometer blade was also penetrated into the sand to the same depth as the aluminum block.

As indicated earlier, the scope of this study covered three sands with different particle shape characteristics from extremely angular (mine tailings) to subrounded (Ottawa sand), with a local dune sand included to represent the intermediate particle shape properties. The degree of angularity of Ottawa, dune, and mine tailings sand particles was determined as 100 to 199, 400 to 499, and 1000 to 1099, respectively, according to the Krumbein charts (2) on visual examination of the particles under a microscope. Before penetration testing, the sand specimens were deposited by pluviation through a funnel and were subsequently compacted by lateral tamping to nominal relative densities of 15, 30, and 45 percent. Actual relative density was determined in each test by measuring the height of the sand after the application of the overburden pressure. At each nominal density, tests were performed under simulated overburden pressures of 12.5, 25, 50, and 100 kPa. With the block, complete pressure-deflection curves between 0- and 1-mm deflection of the diaphragm center were taken twice; the first time while the block was flush with the face plate, the second time after the block was advanced laterally 7 mm into the soil. This information was supplemented with intermediate  $p_0$  readings taken while the block was advanced 2 and 4 mm into the soil. With the regular flat dilatometer,  $p_0$  and  $p_1$  readings were taken after penetration.

A total of 36 tests were performed, four at each nominal test relative density for each sand. In addition, direct shear tests were conducted to determine the range of internal friction angle for the sands used.

## PRESENTATION AND DISCUSSION OF RESULTS

The discussion in this section pertains to relating the dilatometer test data to various parameters of significance from the engineering design point of view such as

- At-rest lateral earth pressure coefficient ( $K_0$ ),
- Horizontal subgrade reaction coefficient ( $k_h$ ), and
- Soil modulus ( $E_s$ ) for lateral loading.

### Lateral Earth Pressure Coefficient ( $K_0$ )

The lateral earth pressure coefficient was calculated from the test data as the ratio of  $p_0$  obtained with the block for the at-rest condition (block flush with the face plate) to the overburden pressure applied. Average values of  $K_0$  for Ottawa, dune, and mine tailings sands were determined as 0.58, 0.51, and 0.35, respectively. The set of  $K_0$ -values (0.45, 0.44, and 0.36) was obtained for the same sands using the angle of friction determined from direct shear tests and the approximate formula  $K_0 = 1 - \sin \phi$  (3).

The literature contains two correlations between dilatometer test data and  $K_0$ ; the first was developed by Marchetti (4), and the second by Schmertmann (5) based on chamber test data. The Marchetti correlation was developed as a result of a series of in situ tests on uncemented clays. The Schmertmann correlation applies specifically to normally and overly consolidated sands. In both cases, the test data were related to  $K_0$  through a calculated parameter ( $K_D$ ), the "horizontal stress index."  $K_D$  is defined as the ratio of ( $p_0 - u_0$ ) to the vertical effective stress. In dry sand,  $u_0$  will naturally be zero. The major difference between these correlations is that Marchetti's empirical formula,  $K_0 = (K_D/1.5)^{4.7} - 0.6$ , shows that  $K_0$  will increase as  $K_D$  increases whereas Schmertmann's correlation indicates that  $K_0$  actually decreases as  $K_D$  increases substantially with friction angle.

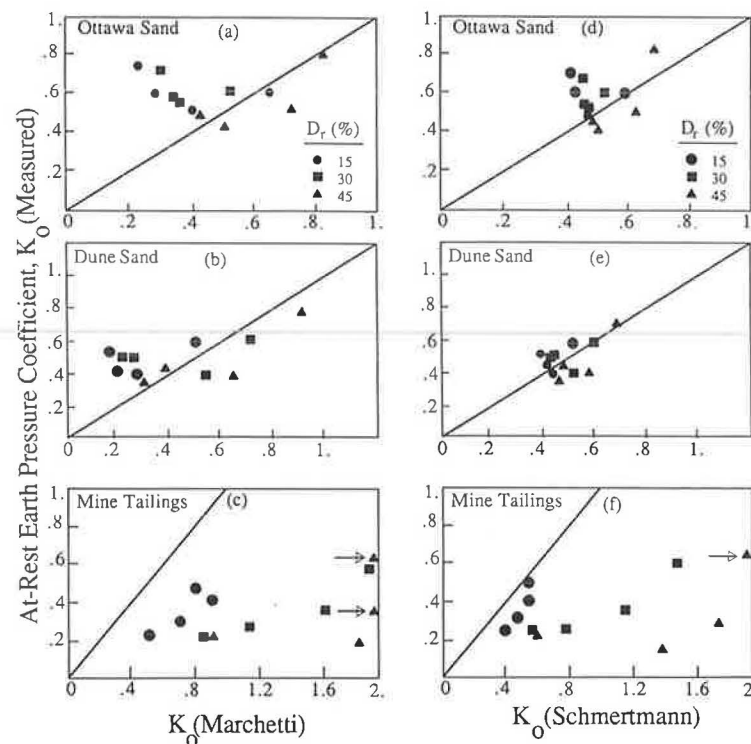


FIGURE 2 Comparison of measured at-rest lateral earth pressure coefficient values with those obtained from Marchetti's formula and Schmertmann's procedure.

Schmertmann recommends the use of his procedure for predicting  $K_0$  in soils with a material index ( $I_D$ ) greater than 1.2, where  $I_D = (p_1 - p_0)/p_0$  for dry sand. The range of material index values in this study varied between 1.43 and 3.94 for Ottawa sand, 2.31 and 4.60 for dune sand, and 1.72 and 3.35 for the mine tailings sand.

As can be seen in Figures 2a–2f, when Schmertmann's correlation is applied the scatter around the equal  $K_0$  lines, clearly visible for the Marchetti correlation, is significantly reduced. The vertical axis in the figures represents the  $K_0$ -values determined from the lateral pressure measurements using the aluminum block. For mine tailings, however, both techniques predict substantially higher  $K_0$ -values than those experimentally determined, although Schmertmann's method definitely proves to be an improvement in this case also.

Figures 3a–3c present the plots of  $K_0$  versus  $K_D$  for all three sands tested. The curves for Ottawa and dune sands clearly indicate an initially decreasing  $K_0$  versus  $K_D$  followed by a reversal in the trend. This is seen to be the case for all three test relative densities. Behavior of this type is believed to be the result of the volume change tendency of the soil being modified in response to the increasing overburden pressure.

The initial part of the curves (decreasing  $K_0$  with  $K_D$ ) is the result of a tendency toward volumetric decrease, under high overburden pressures, when shear is effected by the penetrating dilatometer blade. Under these conditions, even though a substantial portion of the vertical pressure is transferred in the horizontal direction (large  $K_0$ ), penetrating the dilatometer blade will cause shear, accompanied by volume decrease in the immediate vicinity of the blade, that results in relatively small  $p_0$  and  $K_D$ . On the other side of the minimum point the volume

change tendency reverts from contractive to dilative under small pressures. In this region  $K_0$  and  $K_D$  vary in the same direction.

A somewhat different relationship (Figure 3c) represents the mine tailings sand test data. For the same overburden pressure, at-rest  $p_0$ -readings from the block were significantly lower than

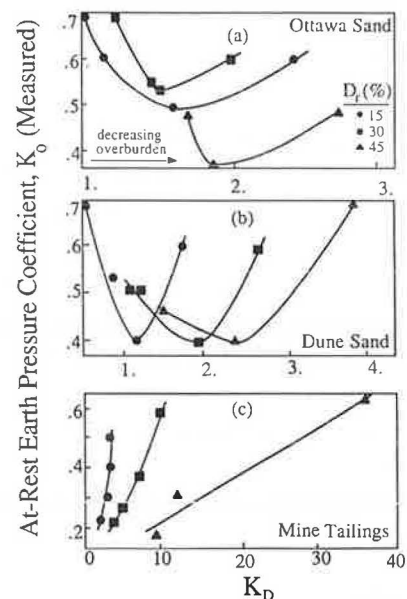


FIGURE 3 Measured at-rest lateral earth pressure coefficient as a function of the horizontal stress index ( $K_D$ ).

$p_0$ -values measured with the other sands, whereas the  $p_0$ -readings from the regular dilatometer blade were significantly higher. Here the volume change tendency is apparently dilative regardless of overburden pressure. The effect of relative density, however, is much more pronounced in mine tailings sand than in the other two sands tested.

The preceding discussion indicates that a generalized relationship between  $K_0$  and  $k_D$  should involve terms to account for the effects of relative density, particle shape characteristics, and overburden pressure. The authors recognize that an effort to derive such a relationship requires a substantially larger sized study than the one presented herein. At first sight, it appears to be somewhat out of the ordinary to include overburden pressure, which is not a physical parameter of soil, in such a relationship. The modifying effects, however, of overburden pressure on the volume change behavior of soil in response to blade penetration, and ultimately on the estimated value of  $K_0$ , cannot be overlooked.

### Coefficient of Horizontal Subgrade Reaction ( $k_h$ )

Analysis of soil response in problems involving loading of soil in the lateral direction, such as laterally loaded vertical piles, is usually performed using the coefficient of horizontal subgrade reaction ( $k_h$ ). This is a parameter based on an artificial concept of modeling soil behavior by a bed of equally spaced and compressible springs, each one independent of the others (6). However, given the usual complexity of the soil-structure interaction problems, its use may often be necessary.

Although the present design of the flat dilatometer does not allow for obtaining  $k_h$  directly, the dilatometer data can provide

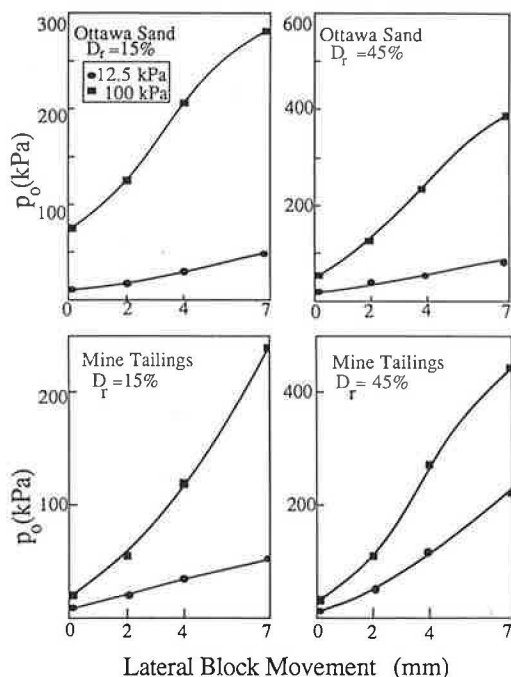


FIGURE 4 Typical  $p_0$  versus lateral block movement curves for Ottawa and mine tailings sands.

for the estimation of  $k_h$ . The response of the undisturbed soil to lateral separation can be qualitatively observed in Figure 4. These responses were obtained by laterally advancing the block into the soils tested inside the test bin. For Ottawa sand, linear approximation of lateral pressure buildup with increasing separation is reasonable over the range of test relative densities and vertical pressures. The same is true of mine tailings at low relative density and vertical pressure. However, for mine tailings, as the vertical pressure is increased at small relative densities, the  $p_0$  versus lateral block movement relationship tends to show nonlinearity, which is due to densification of sand as a result of the lateral movement of the block. At higher relative densities, this effect is substantially reduced. Instead, continued lateral separation appears to initiate yielding in the soil. The same trend is also noticeable in Ottawa sand to a certain extent at all test relative densities and vertical pressures.

Figures 5a–5c show the block subgrade reaction coefficient ( $k_{hb}$ ) versus the dilatometer subgrade reaction coefficient ( $k_{hd}$ ) for the three sands. The  $k_{hb}$ -values used to plot the figures were obtained by taking the difference between  $p_0$  for at-rest and 7-mm lateral block movement conditions and dividing it by

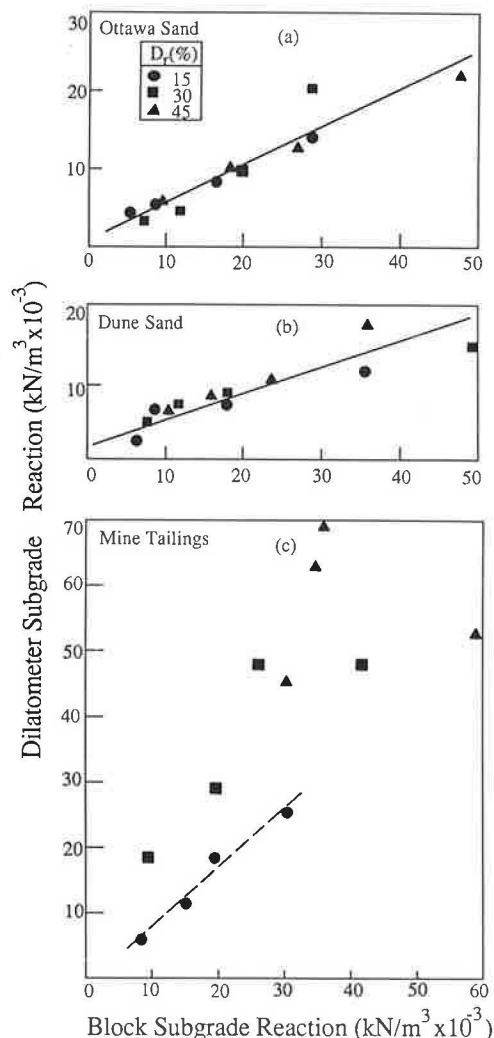


FIGURE 5 Dilatometer versus block subgrade reaction relations for the sands tested.

7 mm, which is half the dilatometer blade thickness. Because no data on the at-rest pressure are readily available in the field, as a first approximation, the  $k_{hd}$ -values were obtained by simply dividing  $p_0$  by the separation distance (7 mm) to reflect this condition. Schmertmann (7) suggests an approximation to relate the subgrade reaction coefficient obtained with a standard dilatometer to the subgrade reaction coefficient adjusted to the pile width for lateral response analyses of piles.

Because of the soil disturbance resulting from the penetration of the blade, the  $k_{hd}$ -values obtained from the standard dilatometer data were significantly different from those obtained with the block. As can be seen in Figure 5, the plot of subgrade reaction values obtained with the dilatometer and the block indicates approximately a straight line relationship for Ottawa and dune sands with little dependence on relative density. In the case of mine tailings, the data plot approximately as a straight line at low relative densities. However, with increasing relative density, the straight line approximation is no longer valid.

The slope of the lines in Figure 5 has been termed the "disturbance index" (1) and represents the correction factor by which the standard dilatometer  $k_{hd}$ -value should be divided to obtain the disturbance-free  $k_h$  (obtained by the aluminum block). This value was found to be approximately 0.48 for Ottawa sand, 0.28 for dune sand, and 1.0 for mine tailings at low relative densities. The coefficient of correlation obtained from linear curve-fitting was 0.95 and 0.91 for Ottawa and dune sands, respectively. In mine tailings, at higher relative densities, the  $k_{hd}$ -value obtained from the dilatometer may actually need to be reduced to represent the disturbance-free  $k_h$ .

In addition to linear regression, despite a limited amount of data, a two-parameter statistical formulation in the form of

$$k_h = a \cdot \sigma_v^b \cdot D_r^c \quad (1)$$

or

$$\log k_h = \log a + b \cdot \log \sigma_v + c \cdot \log D_r \quad (2)$$

where

- $k_h$  = horizontal subgrade reaction coefficient (obtained with the block),
- $a, b, c$  = coefficients,
- $\sigma_v$  = effective overburden pressure, and
- $D_r$  = relative density

was attempted to relate  $k_h$  for undisturbed in situ conditions to the test variables. It was assumed in the selection of the relationship that the effects of the variables involved were multiplicative rather than additive. The following table gives the coefficients  $a$ ,  $b$ , and  $c$  and the correlation coefficient for the three logs. The correlation coefficient was calculated using the logarithmic form in Equation 2.

Soil Type	$a$	$b$	$c$	Correlation Coefficient
Ottawa sand	4609	0.620	0.780	0.994
Dune sand	2467	0.705	0.478	0.974
Mine tailings	13754	0.423	0.637	0.918

The formulation requires that the vertical pressure and the relative density be known, so that  $k_h$  can be estimated. Because it may not always be possible to estimate these parameters reliably in the field, the significance of the statistical relation assumed and the coefficients determined does not go much further than simply indicating the relative importance of each parameter included.

The overconsolidation ratio is estimated to be another contributing factor in the type of formulation described. Because of the nature of the specimen preparation used in this study, however, it was not possible to assess the overconsolidation ratio accurately enough for inclusion in the analysis.

The empirical formula introduced (Equation 2) was used once again in the same form but this time to extract the in situ lateral stress from the standard dilatometer measurements of  $p_0$ . The dependent variable chosen on the left side was  $p_0/(p_0 - \sigma_h)$ , where  $\sigma_h$  is the lateral in situ effective stress. The  $a$ ,  $b$ , and  $c$  coefficients determined (following table) yield reasonably good estimates for Ottawa and dune sands within the bounds of the experimental data obtained. In mine tailings sand, however, despite a relatively high correlation coefficient, for certain combinations of overburden pressure and relative density the formula predicts negative lateral stress due to the small magnitude of  $\sigma_h$  in comparison with  $p_0$  (coupled with statistical uncertainty in the data).

Soil Type	$a$	$b$	$c$	Correlation Coefficient
Ottawa sand	0.361	0.254	-0.490	0.670
Dune sand	0.386	0.254	-0.397	0.867
Mine tailings	0.889	0.019	-0.080	0.864

#### Dilatometer Modulus and Lateral Soil Modulus

A second approach to predicting soil response under lateral loading in soil-structure interaction problems is to use analytical models to represent the structure and the surrounding soil and solve the interaction equations (8). This method requires knowledge of the soil modulus as well as of the structural rigidity. The following discussion centers on relating the lateral soil modulus to the dilatometer modulus measured in the field. Marchetti (4), assuming linear elasticity, defined a "dilatometer modulus" ( $E_D$ ) that can be calculated with the data obtained during the expansion of the diaphragm against the soil as

$$E = \frac{E_s}{1 - \mu^2} = \frac{2D \cdot \Delta p}{\pi \cdot s} \quad (3)$$

where

- $E_s$  = soil "elastic" modulus,
- $\mu$  = Poisson's ratio of soil,
- $D$  = diaphragm diameter,
- $s$  = deflection of diaphragm center, and
- $\Delta p$  = difference between  $p_1$  and  $p_0$ .

During the testing program the dilatometer modulus was obtained three times for each test:



1. With the block for at-rest condition,
2. With the block after 7-mm lateral movement, and
3. With a standard dilatometer.

The values obtained in 1 and 3 yielded the relationships that relate the in situ undisturbed lateral soil modulus to the dilatometer modulus, whereas comparison of the data obtained in 2 and 3 indicated the extent of soil disturbance after penetration of the blade and the resulting vertical shear deformations in soil in the immediate vicinity of the blade in addition to a total of 14-mm lateral separation of the soil.

Given the generally nonlinear stress-strain response of soils, the modulus values obtained in 1, 2, and 3 are actually secant moduli within 0- to 1-mm deflection range of the diaphragm center. At all three relative densities in all three sands, however, no significant nonlinearity was observed on the pressure-deflection curves taken before the lateral movement of the block. This indicates that if the diaphragm inflation were to be started at at-rest conditions, the deflection range of the diaphragm would be too small to detect the nonlinearity in the pressure-deflection curve that would surely occur at larger deflections. In light of the fairly linear  $p_0$  versus the lateral block movement curves presented in the preceding section, it is evident that an essentially linear soil response against lateral separation continues to be the case at substantially larger strains than the diaphragm can impose on the soil when expanded.

Apparently increased stiffness of the soil for small deflections of the diaphragm was obtained after advancing the block 7 mm laterally (Figure 6). This is thought to be the result of the significant soil strains being largely confined to the volume immediately adjacent to the blade stiffened by densification on lateral movement of the block. At larger diaphragm displacements, with increasing volumes of soil affected by the strains due to diaphragm expansion, the response assumes essentially a linear form with substantially reduced slope. Reducing the chamber pressure results in a much steeper return curve, with most of the diaphragm center deflection being nonrecoverable, that indicates that a second loading cycle will result in a substantially increased soil modulus. Continuous recording of

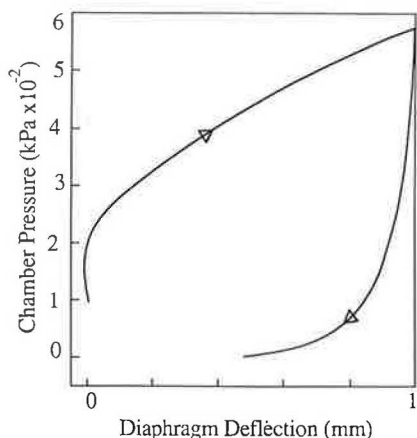


FIGURE 6 Typical chamber pressure versus diaphragm deflection curve taken with the block after 7 mm of lateral movement of the block.

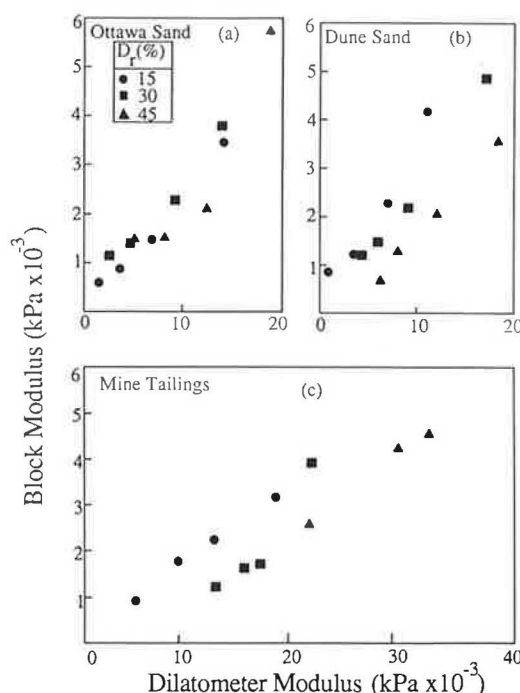


FIGURE 7 Block versus flat dilatometer modulus relations for the sands tested.

the pressure-diaphragm deflection curve during a dilatometer test therefore appears to be of advantage when the soil response under repeated pressurizing of the diaphragm is of interest.

The soil stiffness for small-strain lateral response analyses can be obtained from a relationship between the dilatometer modulus and the at-rest condition lateral soil modulus. A reasonable estimate of the Poisson's ratio, however, is required if the actual value of the soil modulus is sought. The relationships between the moduli obtained in this study are shown in Figure 7. The scatter in data for Ottawa and dune sands leaves uncertainty about the type of the relationship, although particularly in Ottawa sand some nonlinearity is evident. The slope of the curves appears to be dependent on the sand type; higher values for the dilatometer modulus result for mine tailings for the same at-rest lateral soil modulus whereas the results from Ottawa and dune sands are comparable. Correlation coefficients determined with the straight-line assumption were 0.93, 0.81, and 0.93 for Ottawa, dune, and mine tailings sands, respectively. Such relationships can be used effectively in estimating the soil modulus for interaction analyses that require the relative stiffness of the surrounding soil compared with that of the structure.

The statistical regression formula in Equation 2 was also used here to determine the coefficients  $a$ ,  $b$ , and  $c$ . The formula relates the at-rest condition lateral soil modulus to the overburden pressure and the relative density. The results are given in the following table.

Soil Type	$a$	$b$	$c$	Correlation Coefficient
Ottawa sand	2740	0.612	1.01	0.989
Dune sand	96	0.766	-0.146	0.962
Mine tailings	1675	0.356	0.609	0.809

## CONCLUSIONS

The following conclusions, based on the test results reported in this study, can be drawn:

- In estimating  $K_0$ , Schmertmann's technique, which accounts for the friction angle of the sand, gives superior results compared with the original empirical correlation proposed by Marchetti. Both techniques appear to work better with normally consolidated sands.
- For subrounded to subangular sands, the relationship between the at-rest lateral earth pressure coefficient ( $K_0$ ) and the horizontal stress index ( $K_D$ ) appears to be a function of overburden pressure as well as test relative density. This means that the depth of penetration testing should also be considered a factor in evaluating dilatometer data for the in situ lateral earth pressure coefficient. Establishing the exact nature of the relationship for such soils, however, requires extensive experimental and analytical effort.
- For sands largely composed of subrounded to subangular particles, the disturbance index appears to be independent of in situ relative density and overburden pressure. The implication is that the in situ dilatometer test results for such sands can be used to obtain the disturbance-free lateral subgrade reaction coefficient with relatively high accuracy. In sands with angular particles, however, the relation between the dilatometer subgrade reaction coefficient and the disturbance-free lateral subgrade reaction coefficient is influenced by relative density and overburden pressure. Further research is needed to define the disturbance index more accurately over a broad range of soil, density, and in situ stress conditions.
- The relationship between the dilatometer modulus and the at-rest condition soil modulus (block modulus) appears to be approximately linear for sands composed of very angular particles. For sands with subrounded to subangular particles, some nonlinearity is evident. A relationship of this type should be useful in estimating the soil modulus directly from the dilatometer data for soil-structure response analyses.

## REFERENCES

1. E. S. Motan and M. A. Gabr. A Flat-Dilatometer Study of Lateral Soil Response. *Analysis and Design of Pile Foundations: Proceedings of a Symposium on Deep Foundations*, ASCE National Convention, San Francisco, 1984, pp. 232–248.
2. W. C. Krumbein. Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles. *Sedimentary Petrography*, Vol. 11, No. 2, 1941, pp. 64–72.
3. J. Jaky. Earth Pressure in Silos. *Proc., Second International Conference on Soil Mechanics and Foundation Engineering*, Rotterdam, The Netherlands, Vol. 1, 1948, pp. 103–107.
4. S. Marchetti. In-Situ Tests by Flat Dilatometer. *Journal of the Geotechnical Division*, ASCE Vol. 106, No. GT3, 1980, pp. 299–321.
5. J. H. Schmertmann, ed. *DMT Digest No. 1*. GPE, Inc., Gainesville, Fla., 1983.
6. K. Terzaghi. Evaluation of Coefficient of Subgrade Reaction. *Geotechnique*, Vol. 5, No. 4, 1955, pp. 297–326.
7. J. H. Schmertmann, ed. *DMT Digest No. 4*. GPE, Inc., Gainesville, Fla., 1984.
8. H. G. Poulos and E. H. Davis. *Pile Foundation Analysis and Design*. John Wiley and Sons, New York, 1980.

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