#73 STATISTICAL METHODS FOR SOIL LAYER BOUNDARY LOCATION USING THE CONE PENETRATION TEST

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Abstract

The cone penetration test is widely used for the purpose of identification of different soil layers existing in a stratum. The cone bearing, sleeve friction and pore pressure measurements are done at spacings as close as 2.5 cm., and the ensuing parameters such as the friction ratio and pore pressure ratio are used to identify different soil layers. These values are in turn used to determine different soil types from well established soil classification charts. The identification of different layers, based solely on the friction and pore pressure ratios, fails at times and and this paper suggests several statistical methods which can be conveniently used to demarcate layer boundaries. The T ratio and the Intraclass Correlation Coefficient have been used for the univariate analyses and the D^2 statistic for the multivariate analysis. In the univariate case any one of the three parameters, that is, cone bearing, sleeve friction or pore pressure has been used, while in the multivariate analysis, ant two or all three parameters have been simultaneously used for discriminating between different soil layers.

Introduction

The CPT performs data logging at very close intervals and simultaneously measures several channels yielding, for example, values of cone bearing, sleeve friction and pore pressure. The electrical cone penetrometer (CPT) is essentially a logging tool and proper methods of layer identification, should be a high priority. At present, this all important task is performed by visual inspection of the various soil parameter profiles and by studying the variation of the friction ratio, R_f (the ratio between the sleeve friction and the cone bearing). Detailed descriptions of the CPT is given in Campanella et al. (1983).

A low friction ratio with high bearing is evidence of soil which is predominantly sand and a high ratio with low bearing implies a soil which is mainly clay with silty soils lying somewhere between. The ratios obtained are then used together with the cone bearing, to predict the particular type of soil encountered from well established soil classification charts (Fig. 1, Robertson and Campanella - 1986). Prior to entering the charts, the types of layering have to be decided and in certain profiles, a visual inspection alone may not suffice to obtain a fairly accurate estimation of the layer boundaries. The proper identification of soil layering is essential for important decision making in engineering design and construction and subjective estimates as conventionally used today, could lead to erroneous results, especially in cases where distinct differences are not apparent. The classification chart becomes a good tool only if distinct layers are accurately determined and in this regard, statistical methods which differentiate between different types of samples, seem promising.

The statistical methods to be discussed will also enable the engineer to decide on the different number of layers he could select, by inspecting the statistics of the sub-regions within the main layer. If the design requires more detail and sophistication a number of layers based on less critical limits can be chosen, while for a general design for a low risk structure, the layering can be based only on the more critical or the highest peaks of the statistic profile.

Optimal Layer Boundary Location Using Statistical Methods

Consider a section of a transect along which a property such as bearing has been recorded at a number of sampling points and within which the presence of a soil boundary can be expected. The effect of the boundary is to divide the sampling points into two groups which could be then investigated for similarity or dissimilarity. The larger the difference between the two classes and lesser the variation within them, the better is the classification. This effect can be measured using either the T ratio or the interclass correlation coefficient which will be explained later. For multivariate records, the bearing, friction and pore pressure are used together to determine the

D^2 statistic which is used to obtain optimal boundary demarcations.

In analyzing long profiles where the presence of several boundaries are expected it is not practical to consider the entire profile to investigate for individual boundaries. Similarly, it is also not advisable to bracket segments of data arbitrarily. In order to avoid the above difficulties, a 'window' of fixed width (W_D) is made use of and the exposed portion of the data within the window is examined, with the center point of the window d_o, being a potential boundary. This 'window' is moved along the profile in steps equal to the sampling spacing and at each point d_o (the center of the window), the two sets of data one above and one below d_o is examined for distinctness, using any one of the recommended statistics; the T statistic or the Intraclass Correlation Coefficient for univariate data and the D^2 for multivariate data. The variation of the above statistics are plotted against d_o, with the maxima or peaks of these giving the optimal layer boundaries. If only the layers whose characteristics are highly dissimilar are required only those d_o values which have the highest values of the statistic need be chosen. However, if a more elaborate layer identification is necessary, even d_o values giving moderately high values should be selected.

The width of the window is another matter of concern and it should ideally lie between two limits. It should not be too wide, so that it includes more than one boundary and on the other hand should not be too narrow, because if it so the values of the statistic will be strongly influenced by noise, rendering any interpretations from the variation calculated, almost impossible. Webster (1973) has found from experience that it is best to have the window width approximately two thirds of the expected distance between boundaries. However, if the spacing between boundaries differ significantly, it is recommended to use a fairly low window width, to avoid missing any layer boundaries. The expected distance or the average distance between layer boundaries could be obtained from an autocorrelation analysis. If relatively sharp changes are present between soil types and the distance between layers do not change too much the autocorrelation function will decrease steadily with increasing lag distance, from a maximum of unity to a minimum value and fluctuate around this minimum. In practice the autocorrelation function first decreases gradually, and then fluctuates around some minimum, giving several local maxima and minima. The distance at which the first minimum is reached can be taken as the expected distance. As mentioned previously, two thirds of this distance is a safe estimate for the window width.

Univariate Records

The two statistics used to identify soil layers from single records are;

(a) T Ratio
(b) Intraclass Correlation Coefficient (ρ_I)

T Ratio

On either side of any window center d_o, there would be two samples, Ω_1 and Ω_2. Let $\bar{Q_1}$ and $\bar{Q_2}$ be the means of the samples and ${\sigma_1}^2$, ${\sigma_2}^2$ be the variances with n_1 and n_2 the sample sizes respectively, of any one of the three main parameters obtained from the CPT, namely, the cone bearing, sleeve friction or pore pressure.
The variances are given by,

$$ {\sigma_1}^2 = \frac{1}{(n_1 - 1)} \sum_{i=1}^{n_1} (Q_i - \bar{Q_1})^2 \tag{1} $$

$$ {\sigma_2}^2 = \frac{1}{(n_2 - 1)} \sum_{i=1}^{n_2} (Q_i - \bar{Q_2})^2 \tag{2} $$

The pooled within class variance ${\Upsilon_w}^2$ is given by,

$$ {\Upsilon_w}^2 = \frac{n_1}{n_1 + n_2 - 1}{\sigma_1}^2 + \frac{n_2}{n_1 + n_2 - 1}{\sigma_2}^2 \tag{3} $$

In the above equation ${\sigma_1}^2$ and ${\sigma_2}^2$ can be expected to be reasonably homogeneous, since the window widths are reasonably narrow. The T ratio can now be defined as (Webster et al. - 1968),

$$ T = \frac{\bar{Q_1} - \bar{Q_2}}{\Upsilon_w} \sqrt{\frac{n_1 n_2}{n_1 + n_2}} \tag{4} $$

One requirement for the best possible differentiation of any two adjacent layers, is that the difference between the means $(\bar{Q_1} - \bar{Q_2})$, be maximum. If the two samples Ω_1 and Ω_2 are clearly distinct another requirement is that the individual variances of the two segments, ${\sigma_1}^2$ and ${\sigma_2}^2$, be relatively low, implying that the pooled within class variance given by Eq. 3, also is appreciably low. Considering the aforementioned requirements, the T ratio given by Eq. 4, will necessarily have to peak at potential layer boundaries. The T ratio, thus obtained for different values of d_o, gives an indication of the layer boundaries of the profile.

Intraclass Correlation Coefficient

As for the previous case let σ_1 and σ_2 be the variances of samples Ω_1 and Ω_2 and the pooled within class variance ${\Upsilon_w}^2$, given by Eq.3. The between class variance ${\Upsilon_b}^2$ is the variance of the combined sample given by (Webster and Beckett - 1968),

$$ {\Upsilon_b}^2 = \frac{1}{n_1 + n_2 - 1} \sum_{i=1}^{n_1+n_2} (Q_i - \bar{Q})^2 \qquad (5) $$

where, $\bar{Q}$ is the mean of all the data Q_i with $i = 1, 2 \ldots (n_1 + n_2)$.

The Intraclass Correlation Coefficient, ρ_I, is given by,

$$ \rho_I = \frac{{\Upsilon_b}^2}{{\Upsilon_b}^2 + {\Upsilon_w}^2} \qquad (6) $$

It is evident that if each sample Ω_1 and Ω_2 is absolutely uniform then ${\Upsilon_w}^2$ is equal to zero and ρ_I will have its maximum value of unity. If the differences between the samples are not significant then ${\Upsilon_b}^2$ and ρ_I are not significantly greater than zero. ρ_I will always lie between these two extremes and a relatively high value of ρ_I will indicate the presence of a layer boundary at that point. As with the T ratio, the value of ρ_I can be plotted against depth, in order to determine the best layer boundaries along the profile.

Multivariate Records

The CPT performed at UBC, performs data logging on several channels, the cone bearing, sleeve friction and the pore pressure being the most important of these, from an engineering point of view. All these parameters exhibit a different kind of behaviour in different types of soils and therefore any method which considers all the above parameters simultaneously, will definitely be the more efficient and accurate method.

D^2 Statistic

The D^2 statistic gives most weight to those variates that discriminate best between segments. Problems arise if there are several variates, in comparison to the number of data (Rao - 1952). However, in the problems dealt with here, this is not of major concern even for the case of very narrow window widths, since the number of variates do not exceed three.

The use of the discriminant function may be considered in terms of a sample Ω_1 consisting of m variates, which form a cluster of points in m - dimensional space. Another sample Ω_2 may be described similarly by the same m variables in m - dimensional space. The determination of a (m - 1) - dimensional plane that separates the two clusters of points is the discriminant function. The D^2 is the distance between the multivariate means of the two dimensional sample spaces Ω_1 and Ω_2, implying that greater the value of D^2, the more distinct the two samples would be (Rao - 1965, Harbaugh and Merriam - 1968). This is illustrated in Fig. 2, for the case of two variables (m = 2).

The D^2 statistic is given by,

$$D^2 = \{\bar{\mathbf{Q}}_1 - \bar{\mathbf{Q}}_2\}'\mathbf{W}^{-1}\{\bar{\mathbf{Q}}_1 - \bar{\mathbf{Q}}_2\} \tag{7}$$

where, $\{\bar{\mathbf{Q}}_1 - \bar{\mathbf{Q}}_2\}$ is the column matrix of the mean differences of the variates in the two samples. For the case with m variables, $\{\bar{\mathbf{Q}}_1 - \bar{\mathbf{Q}}_2\}$ is a m x 1 matrix.$\{\mathbf{W}\}$ is the pooled variance - covariance matrix of the samples Ω_1 and Ω_2. For layer identification purposes using the cone, the maximum number of variates (m) will be equal to three. Let the set of n_1 data points from Ω_1 and n_2 data points from Ω_2 be described by the following variables;

q_1, f_1, u_1 being the bearing, friction and pore presure in Ω_1

q_2, f_2, u_2 being the bearing, friction and pore presure in Ω_2

The means of the respective parameters in sample Ω_1 are given by, $\bar{q}_1$, $\bar{f}_1$ and $\bar{u}_1$ and for sample Ω_2 by, $\bar{q}_2$, $\bar{f}_2$ and $\bar{u}_2$ and their variances by, ${\sigma_{q_1}}^2$, ${\sigma_{f_1}}^2$, ${\sigma_{u_1}}^2$, ${\sigma_{q_2}}^2$, ${\sigma_{f_2}}^2$ and ${\sigma_{u_2}}^2$.

The mean differences of the variates of the two samples are given by,

$$\Delta q = \bar{q}_1 - \bar{q}_2 \qquad \Delta f = \bar{f}_1 - \bar{f}_2 \qquad \Delta u = \bar{u}_1 - \bar{u}_2 \tag{8}$$

The covariances are given by,

$$\sigma_{q_1 f_1}{}^2 = \frac{\sum_{i=1}^{n_1} q_{1i} f_{1i}}{n_1} - \frac{\sum_{i=1}^{n_1} q_{1i} \sum_{i=1}^{n_1} f_{1i}}{n_1{}^2} \tag{9}$$

$$\sigma_{q_1 u_1}{}^2 = \frac{\sum_{i=1}^{n_1} q_{1i} u_{1i}}{n_1} - \frac{\sum_{i=1}^{n_1} q_{1i} \sum_{i=1}^{n_1} u_{1i}}{n_1{}^2} \tag{10}$$

$$\sigma_{f_1 u_1}{}^2 = \frac{\sum_{i=1}^{n_1} f_{1i} u_{1i}}{n_1} - \frac{\sum_{i=1}^{n_1} f_{1i} \sum_{i=1}^{n_1} f_{1i}}{n_1{}^2} \tag{11}$$

$$\sigma_{q_2 f_2}{}^2 = \frac{\sum_{i=1}^{n_2} q_{2i} f_{2i}}{n_2} - \frac{\sum_{i=1}^{n_2} q_{2i} \sum_{i=1}^{n_2} f_{2i}}{n_2{}^2} \tag{12}$$

$$\sigma_{q_2 u_2}{}^2 = \frac{\sum_{i=1}^{n_2} q_{2i} u_{2i}}{n_2} - \frac{\sum_{i=1}^{n_2} q_{2i} \sum_{i=1}^{n_2} u_{2i}}{n_2{}^2} \tag{13}$$

$$\sigma_{f_2 u_2}{}^2 = \frac{\sum_{i=1}^{n_2} f_{2i} u_{2i}}{n_2} - \frac{\sum_{i=1}^{n_2} f_{2i} \sum_{i=1}^{n_2} f_{2i}}{n_2{}^2} \tag{14}$$

The pooled weighted variances are given by,

$$\Gamma_q{}^2 = \frac{n_1}{n_1 + n_2 - 1} \sigma_{q_1}{}^2 + \frac{n_2}{n_1 + n_2 - 1} \sigma_{q_2}{}^2 \tag{15}$$

$$\Gamma_f{}^2 = \frac{n_1}{n_1 + n_2 - 1} \sigma_{f_1}{}^2 + \frac{n_2}{n_1 + n_2 - 1} \sigma_{f_2}{}^2 \tag{16}$$

$$\Gamma_u{}^2 = \frac{n_1}{n_1 + n_2 - 1} \sigma_{u_1}{}^2 + \frac{n_2}{n_1 + n_2 - 1} \sigma_{u_2}{}^2 \tag{17}$$

Similarly, the pooled weighted covariances are given by,

$$\Gamma_{qf}{}^2 = \frac{n_1}{n_1 + n_2 - 1} \sigma_{q_1 f_1}{}^2 + \frac{n_2}{n_1 + n_2 - 1} \sigma_{q_2 f_2}{}^2 \tag{18}$$

$$\Gamma_{qu}{}^2 = \frac{n_1}{n_1 + n_2 - 1} \sigma_{q_1 u_1}{}^2 + \frac{n_2}{n_1 + n_2 - 1} \sigma_{q_2 u_2}{}^2 \tag{19}$$

$$\Gamma_{fu}{}^2 = \frac{n_1}{n_1 + n_2 - 1} \sigma_{f_1 u_1}{}^2 + \frac{n_2}{n_1 + n_2 - 1} \sigma_{f_2 u_2}{}^2 \tag{20}$$

If equal number of data points are considered for sample Ω_1 and Ω_2 (as usually the case is), $n_1/(n_1 + n_2 - 1)$ and and $n_2/(n_1 + n_2 - 1)$ in Eq. 15 to Eq. 20 can be approximated by 0.5.

The variance covariance matrix $\{\mathbf{W}\}$ can be now formulated and is comprised of the elements derived above (Harbaugh and Merriam - 1968).

$$\{\mathbf{W}\} = \begin{pmatrix} {\Gamma_q}^2 & {\Gamma_{qf}}^2 & {\Gamma_{qu}}^2 \\ {\Gamma_{qf}}^2 & {\Gamma_f}^2 & {\Gamma_{fu}}^2 \\ {\Gamma_{qu}}^2 & {\Gamma_{fu}}^2 & {\Gamma_u}^2 \end{pmatrix} \tag{21}$$

$\{\bar{\mathbf{Q}}_1 - \bar{\mathbf{Q}}_2\}$ in Eq. 7 is given by,

$$\{\bar{\mathbf{Q}}_1 - \bar{\mathbf{Q}}_2\} = \begin{pmatrix} \Delta q \\ \Delta f \\ \Delta u \end{pmatrix} \tag{22}$$

In using the D^2 statistic, to identify soil layer boundaries, the window is moved along the data profile, with d_o the mid-point of the window separating the two samples and for each d_o the value of D^2 is calculated and plotted against depth. The peaks of the ensuing plot would clearly illustrate the best positions of the layer boundaries. If only a few boundaries are needed, the points at which the highest D^2 values occur can be selected. If in the engineer's mind, more layers are needed, the less critical D^2 values too can be used, in order to obtain more layer demarcations.

Application to CPT Profiles

The above concepts of statistically identifying layers have been applied to two sets of data in order to illustrate the advantages of the methods explained above. The locations from which the data have been obtained are;

(a) McDonald Farm Site
(b) Haney Site

All the data have been obtained using a cone of sectional area $10cm^2$ with penetration at 2 cm/sec and data logging being performed at every 2.5 cm of depth.

McDonald Farm Site

The McDonald Farm, typically consists of sand and sandy silts in the top 15 meters with clayey soils extending below the sand. The cone bearing, sleeve friction, pore pressure and friction ratio profiles are illustrated in Fig. 3.

At the outset an autocorrelation analysis was performed for the three variables and the variation of the function with lag distance is illustrated in Fig. 4. The purpose of this , is to determine an optimal window width, W_D, which ideally should lie between two limits: not too wide, in order to avoid the possibility of missing thinner layers and not too narrow, in order to minimize noise in the calculated statistics. The autocorrelation plot in Fig. 4 results in three different initial minimum points for the three variables, indicated by the arrows which read as 6.82 meters for cone bearing, 2.74 meters for friction and 5.22 for pore pressure. The multivariate analysis requires a single value for W_D since all three variables are handled simultaneously, while for the univariate analysis three different widths can be used for the three variables. However, it is always advisable to decide on a single W_D even for the univariate case to facilitate comparisons between variates. The more drastic consequence of choosing an incorrect W_D is that if it is too wide potential layers will be missed and the possibility of this has to be avoided. As explained earlier, the upper limit of the W_D will have to be below the minimum value of 2.74 meters, mentioned above and preferably about two - thirds of 2.74 in order to avoid any possibility of missing any dominant layers. Therefore, the most adequate W_D was selected as 1.5 meters and all the detailed analyses and comparisons to follow, will deal with this window width.

The variations of the Intraclass Correlation Coefficient , ρ_I, with depth, for bearing, friction and pore pressure are illustrated in Fig. 5. The variation of the T ratio for the three properties are given in Fig. 6.

The following depths have been obtained as the most critical layer depths, considering the T Ratio for cone bearing, sleeve friction and pore pressure in Fig. 3.

Cone Bearing : 1.92, 4.35, 6.60, 9.04, 10.02, 11.93, 13.30, 14.50 meters.

Friction : 2.65, 4.32, 6.52, 7.35, 9.05, 9.90, 14.52 meters.

Pore Pressure : 3.12, 4.29, 5.42, 6.47, 8.02, 9.10, 11.97, 14.77 meters.

The results above indicate that all three variables are in agreement with layer boundaries at 4.3, 6.5, 9.05 and 14.6 meters.

For the Intraclass Correlation Coefficient (Fig. 5), the results are as follows;

Cone Bearing : 1.25, 4.35, 6.60, 9.05, 10.02, 11.97, 13.10, 14.50, 15.47 meters.

Friction : 4.32, 6.50, 7.38, 8.98, 9.90, 14.53 meters.

Pore pressure : 4.27, 5.42, 6.47, 9.10, 11.97, 14.77, 16.02, 17.80 meters.

The pore pressure variation gives rise to more fluctuations and therefore more layering could be detected. The layer boundaries that could be selected from the results of the intraclass correlation coefficient are 4.3, 6.5, 9.0 and 14.6 meters and agrees well with those obtained for the T ratio. The depth of 11.97 meters is a boundary where bearing and pore pressure are concerned, although it is not apparent for friction. Similarly, the peak at approximately 10.0 meters is not visible in the profile for pore pressure, while it is evident for friction and bearing.

From the above results it can be concluded that the two statistics, the intraclass correlation and the T ratio are very appropriate statistics for discriminating between layers.

A multivariate analysis was performed for the three variables and the D^2 was calculated. The variation of D^2 is illustrated in Fig. 7 and it can be seen that the peaks occurring at the depths of 4.3, 9.1 and 14.6 are very prominent. Another possible but less dominant layer boundary can be found at 10.0 meters. These results agree very well with the ones obtained for the univariate analyses.

It is widely accepted in geotechnical circles, that the friction ratio is a reliable method for identifying different layers in a soil stratum. It may be so for certain profiles, but as the friction ratio (R_f) profile in Fig. 3 indicates, it is not so for the profile under consideration. According to the method practiced to-day, the value of the friction ratio is the indicator of the soil type, implying that the point at which a marked difference of the R_f takes place, is a layer boundary. The R_f profile definitely does not recognize the layer boundary at approximately 9.0 meters although the boundary at 4.3 meters is picked up. Furthermore, a comparison of the R_F profile with the figures illustrating the variation of the statistics already described, clearly exemplify the advantages of the latter. In the statistical method, the high peaks are the layer boundaries and can be clearly picked out while in the R_f method it is not very easy to select layers with approximately equal friction ratios.

Haney Site

The cone bearing, sleeve friction, pore pressure and friction ratio profiles of the Haney site are illustrated in Fig. 8.

An autocorrelation analysis was performed on the three variables and the expected layer thicknesses were not similar. The lowest value was obtained for friction with a value of approximately 3.0 meters. Therefore, a window width W_D, of 2.0 meters was selected, with the main purpose of this defined width being to avoid the possibility of missing layer boundaries.

The Intraclass Correlation Coefficient , ρ_I, was calculated and the best layer boundaries for the three variables (Fig. 9)are as follows;

Cone Bearing : 2.13, 7.70, 9.30, 11.80, 15.95, 17.93, 19.85 meters.

Friction : 2.13, 3.93, 7.88, 9.28, 11.55, 12.65, 15.95, 17.83 meters.

Pore Pressure : 1.23, 4.38, 6.73, 7.78, 9.30, 10.90, 11.88, 12.70, 15.87, 17.93, 19.83 meters.

The T Ratio profile (Fig. 10), agrees with the layer boundaries obtained from the Intraclass Correlation Coefficient .
The D^2 determination, considering all three variables, resulted in the following layer boundaries (Fig. 11);

7.75, 9.30, 12.68, 15.95 and 17.93 meters.

The friction ratio R_f profile for the Haney data is illustrated in Fig. 8 and sharp variations of R_f values could be observed at depths of 7.75 and 12.68 meters, giving rise to layer boundaries at these points. This is in agreement with the statistical determinations, although the boundaries at 9.30, 15.95 and 17.93 meters are not picked up, or at least not clearly apparent from the R_f profile in Fig. 8. In contrast to the R_f profile, the other statistical profiles, namely the Intraclass Correlation Coefficient , T ratio and especially the D^2, recognize the layer boundaries very distinctly and conveniently.

Conclusions

The three examples described above, provide sufficient evidence why statistical methods should be employed in identifying layer boundaries. These statistical methods using univariate (Intraclass Correlation Coefficient and T Ratio) and multivariate (D^2) methods have a sound fundamental basis for discriminating between different sample types or different layers. In all three cases investigated, some of the depths obtained by the statistical methods agreed well with the R_f method and could be easily observed from the profile, while some depths were not very apparent. However, a closer examination of the cone bearing, pore pressure and friction ratio profiles seem to agree favorably with most of the depths obtained from the statistical methods. If a statistical method was not used, these additional boundaries could not have been recognized merely from the soil parameter profiles. If the R_f method is considered fairly satisfactory in predominantly sandy soils it is not adequate at all, to differentiate between sublayers in mainly clayey soils. Considering all of the above and the examples described, the statistical methods qualify at least as a good supplement to the conventionally used friction ratio method, if not a more efficient alternative, in obtaining soil layer boundaries.

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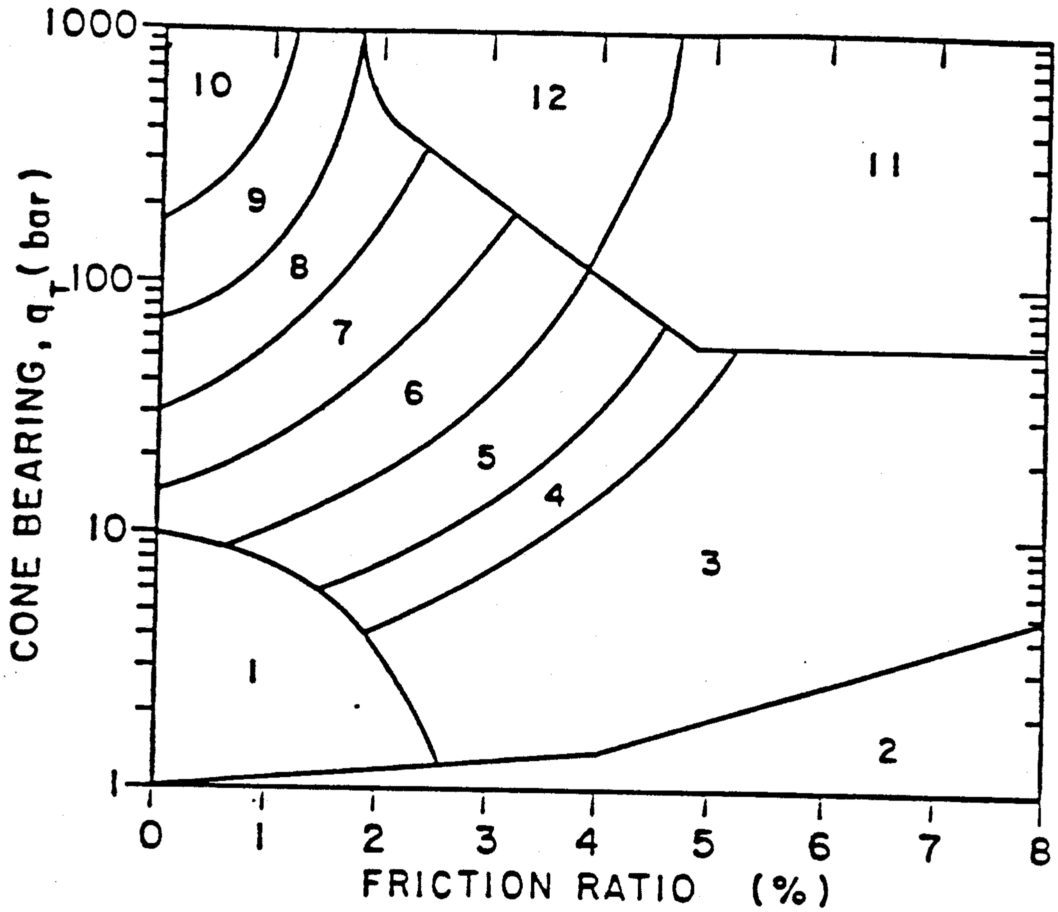

Zone	Qc/N	Soil Behaviour Type
1)	2	sensitive fine grained
2)	1	organic material
3)	1	clay
4)	1.5	silty clay to clay
5)	2	clayey silt to silty clay
6)	2.5	sandy silt to clayey silt
7)	3	silty sand to sandy silt
8)	4	sand to silty sand
9)	5	sand
10)	6	gravelly sand to sand
11)	1	very stiff fine grained (*)
12)	2	sand to clayey sand (*)

(*) overconsolidated or cemented

Figure 1 : Simplified Soil Classification Chart for the CPT (after Robertson, 1985)

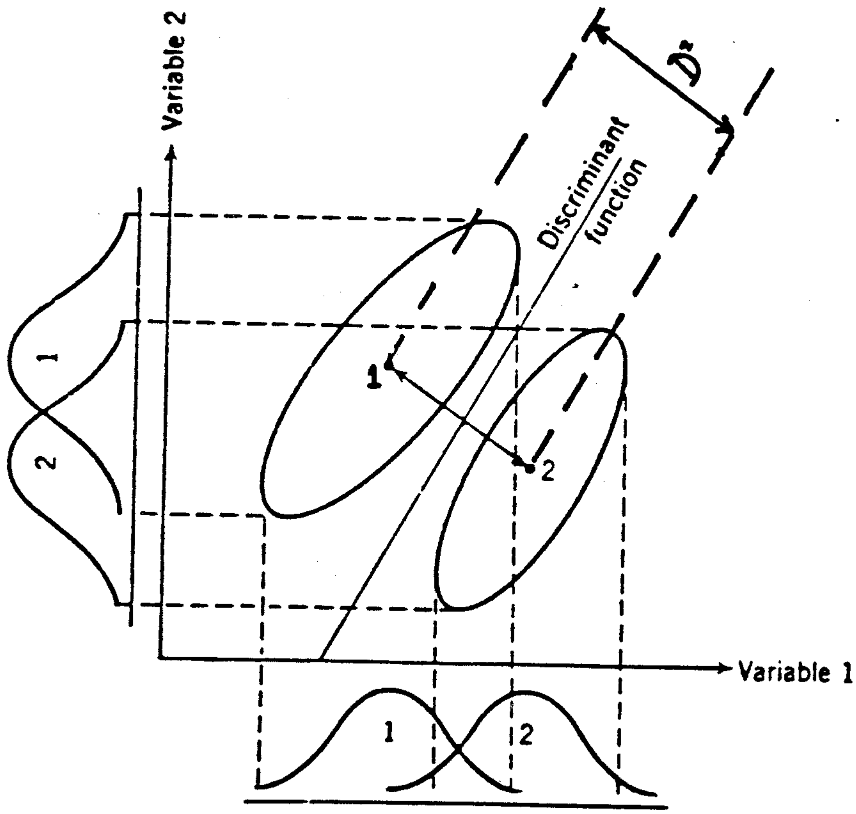

Figure 2: Discriminant Function Between Two Bivariate Populations (after Harbaugh and Merriam, 1968).

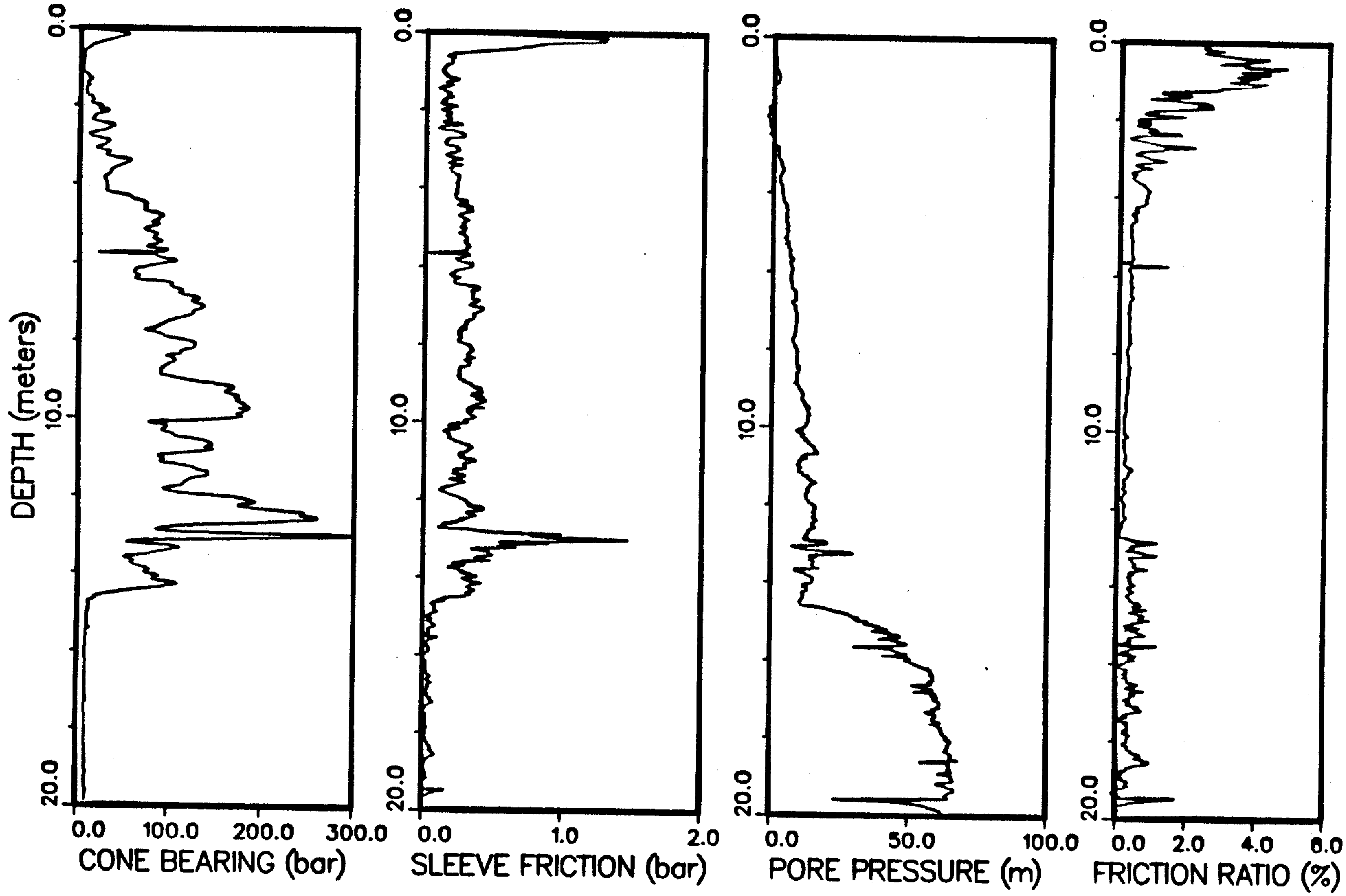

Figure 3. Cone Bearing, Sleeve Friction, Pore Pressure and Friction Ratio Profiles at McDonald Farm.

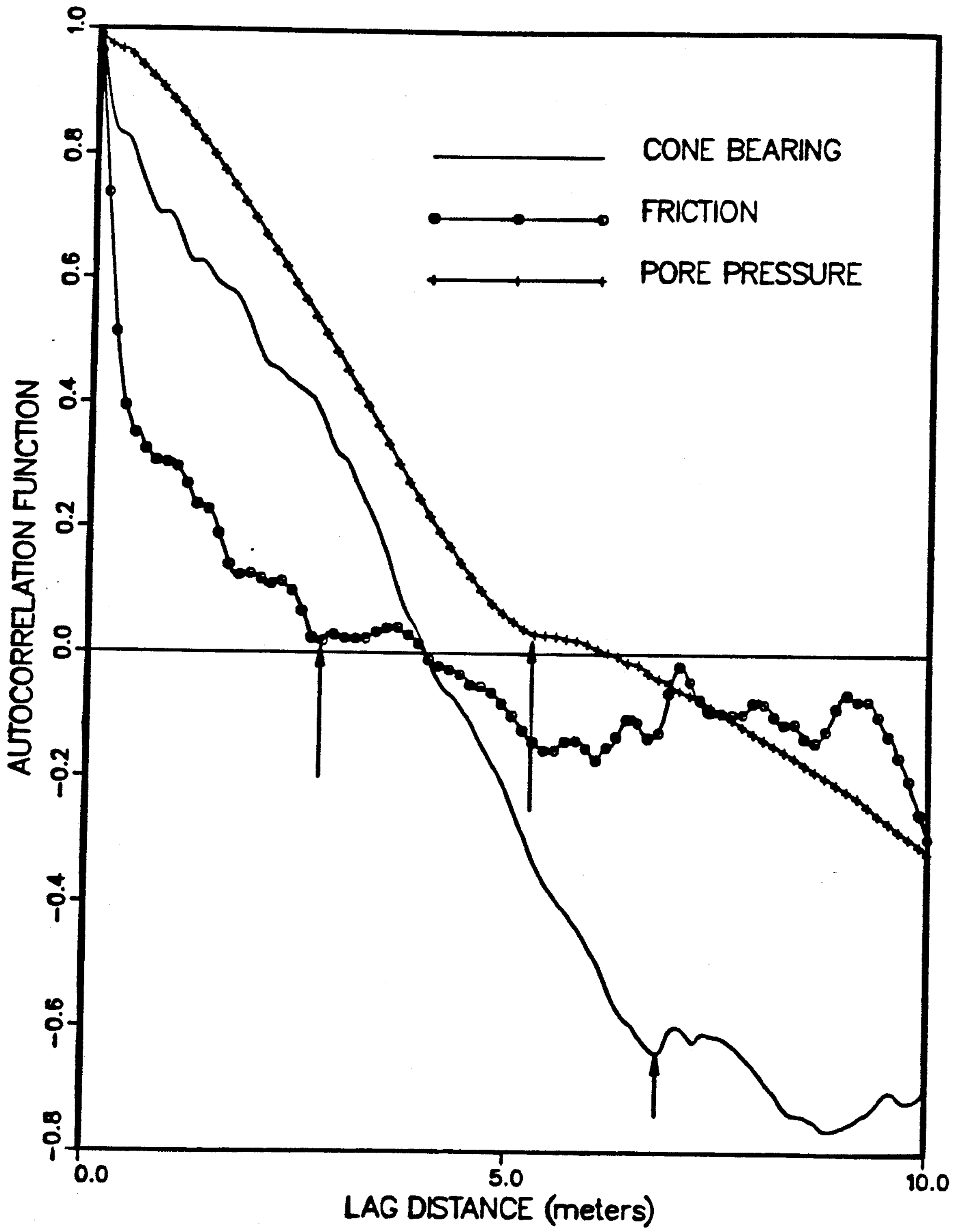

Figure 4: Autocorrelation Functions of Cone Bearing, Sleeve Friction and Pore Pressure Profiles at McDonald Farm.

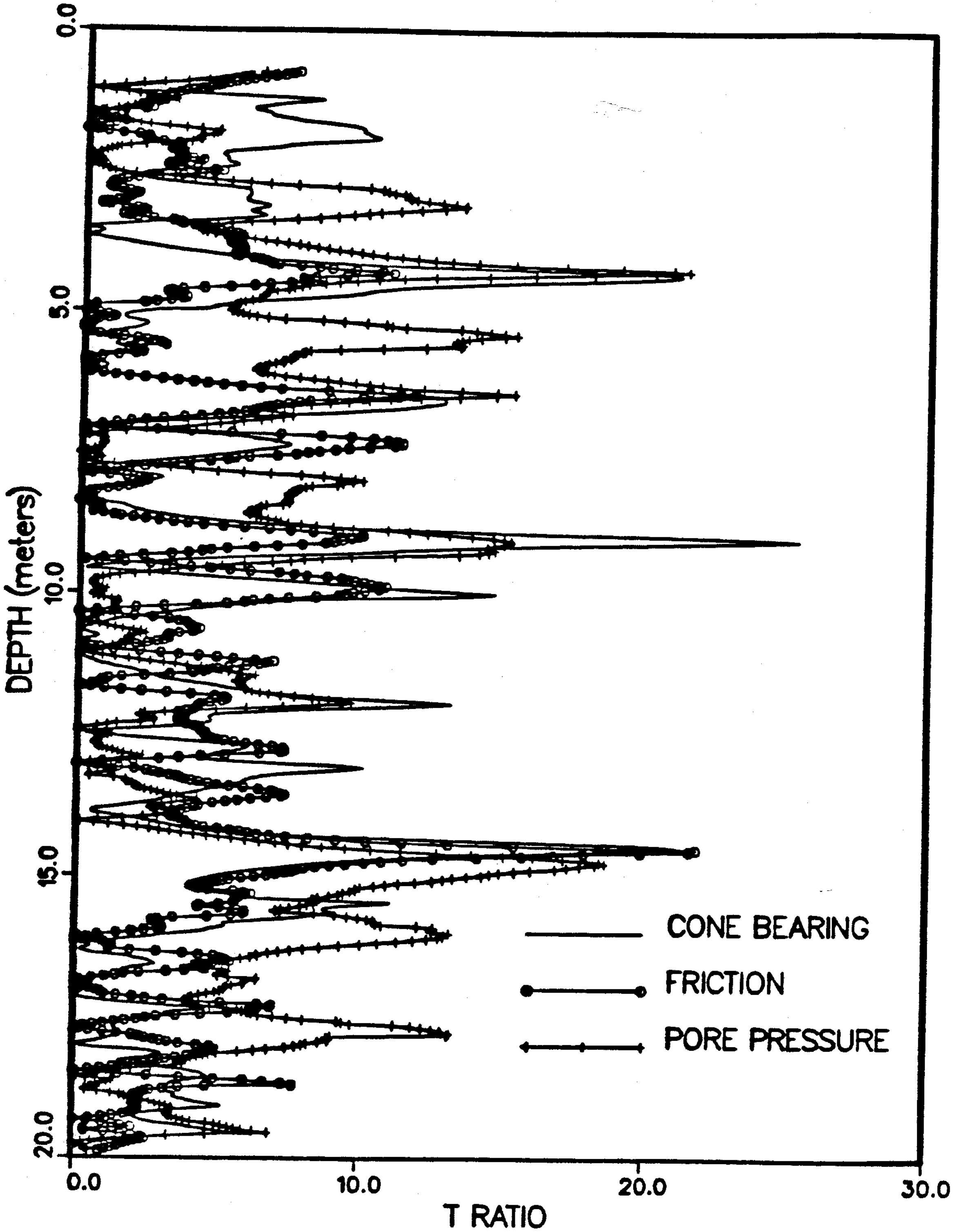

Figure 5 : T Ratio for Cone Bearing, Friction and Pore Pressure at McDonald Farm for a Window Width of 1.5 meters.

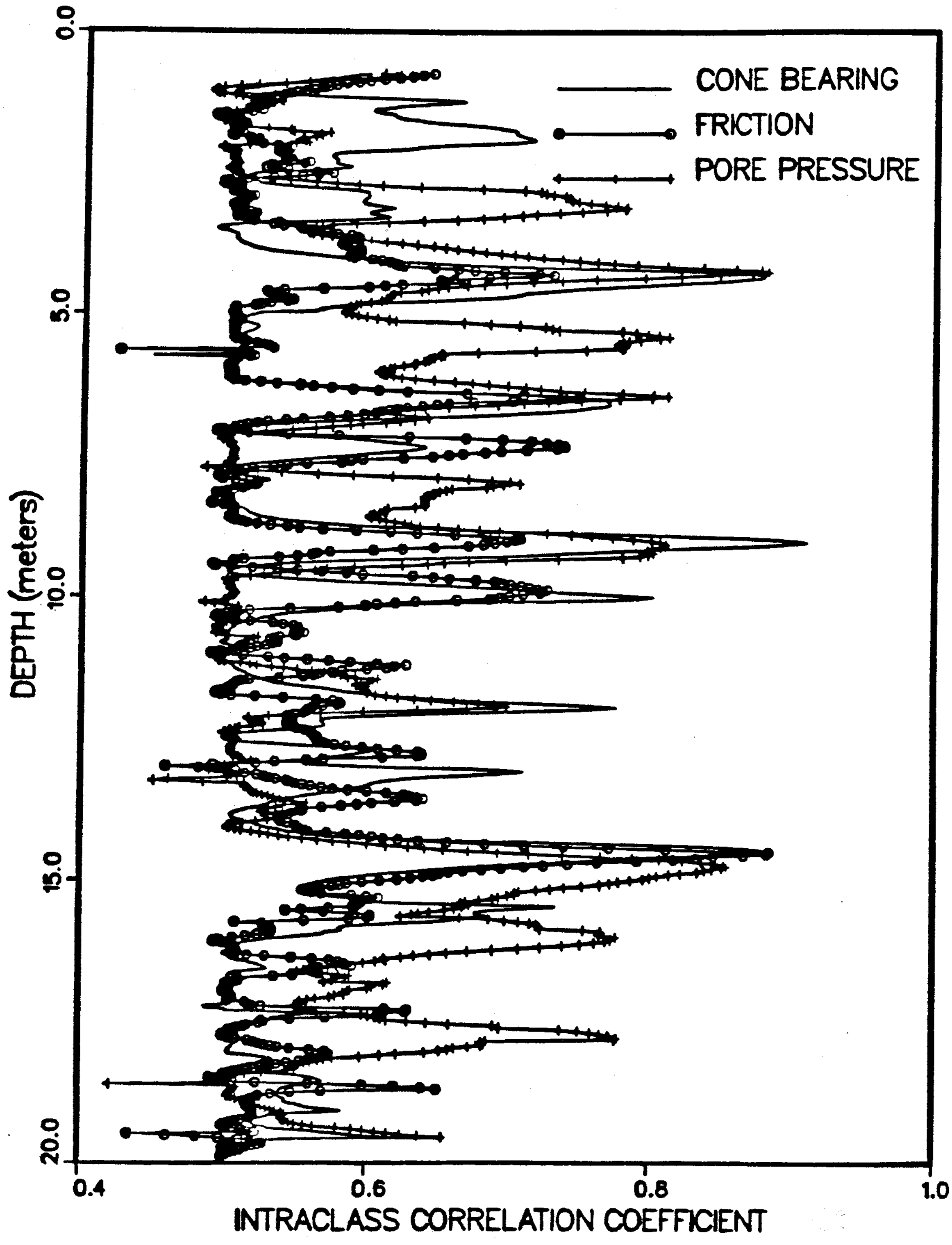

Figure 6: Intraclass Correlation Coefficient for Cone Bearing, Friction and Pore Pressure at McDonald Farm for a Window Width of 1.5 meter.

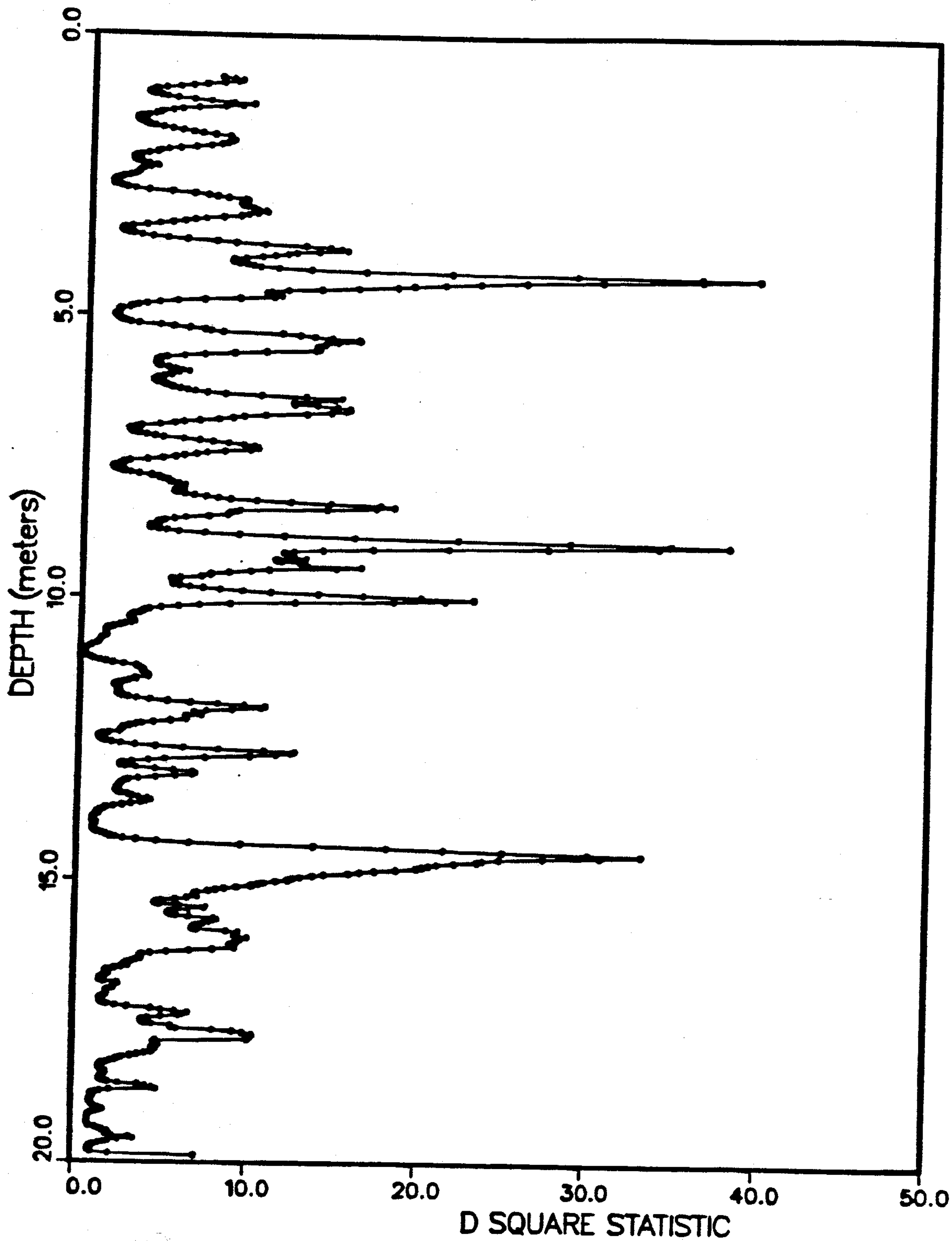

Figure 7 : D^2 Statistic of Multivariate Analysis at McDonald Farm for a Window Width of 1.5 meters.

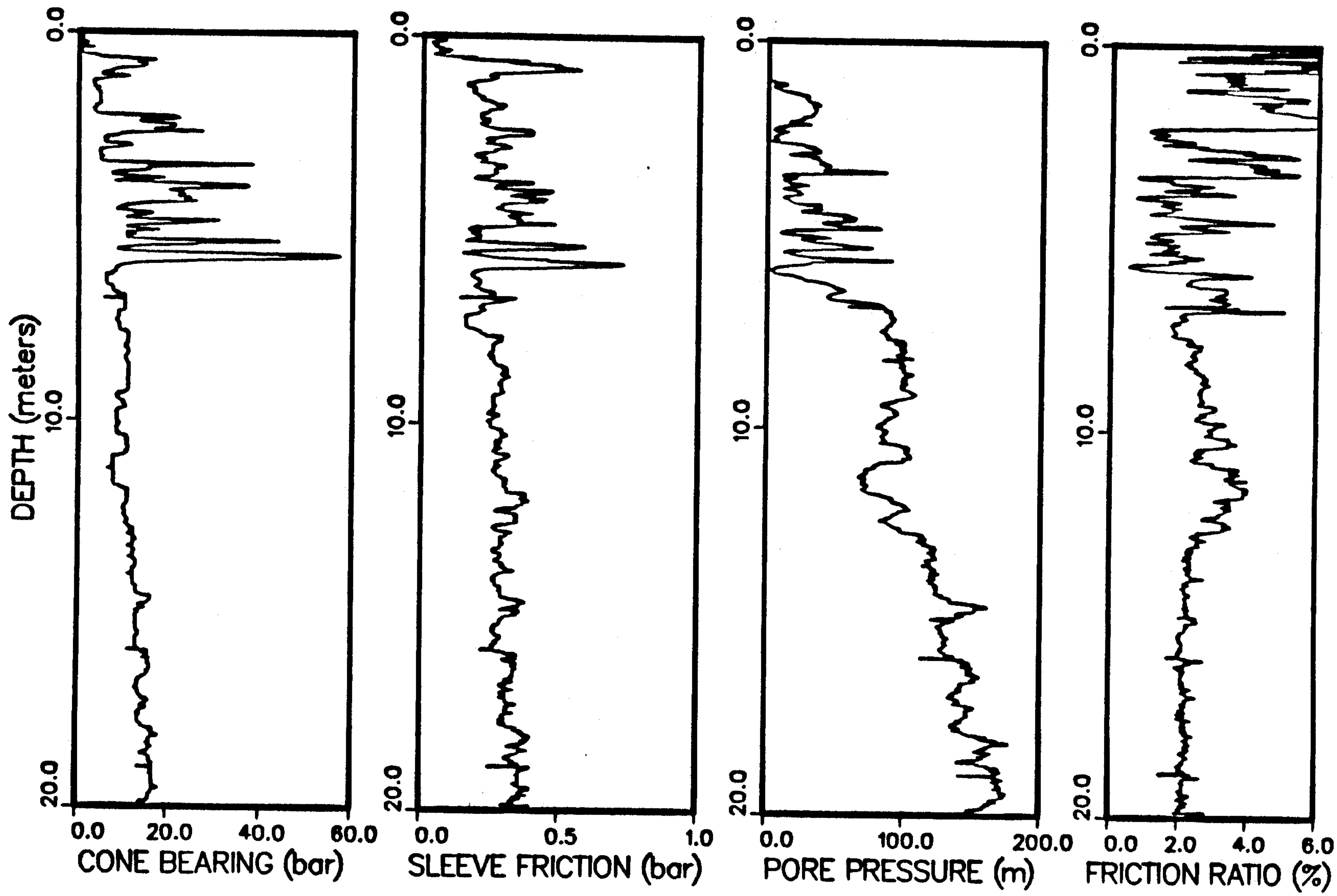

Figure 8: Cone Bearing, Sleeve Friction, Pore Pressure and Friction Ratio Profiles at Haney Site.

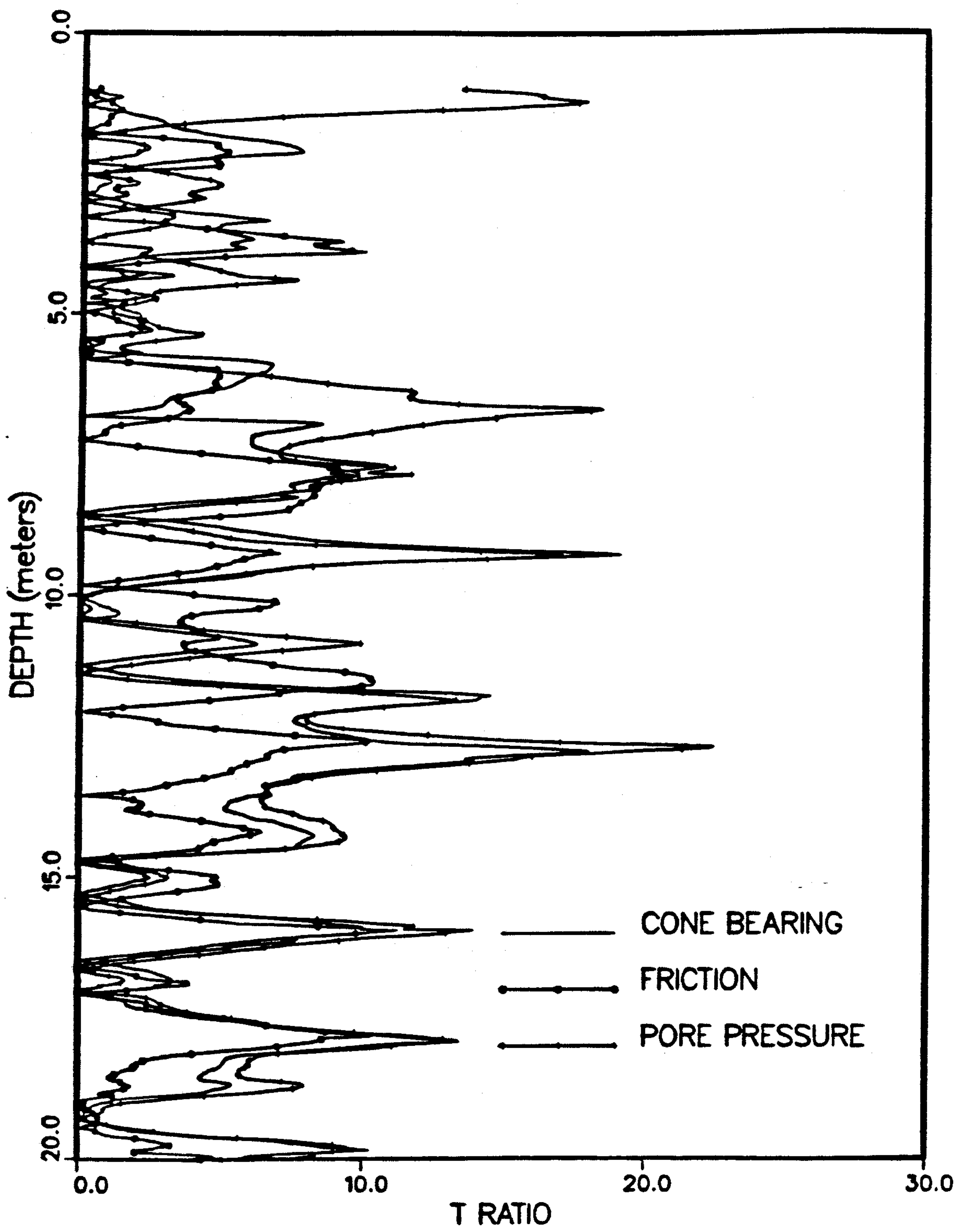

Figure 9 : T Ratio for Cone Bearing, Friction and Pore Pressure at Haney Site for a Window Width of 2.0 meters.

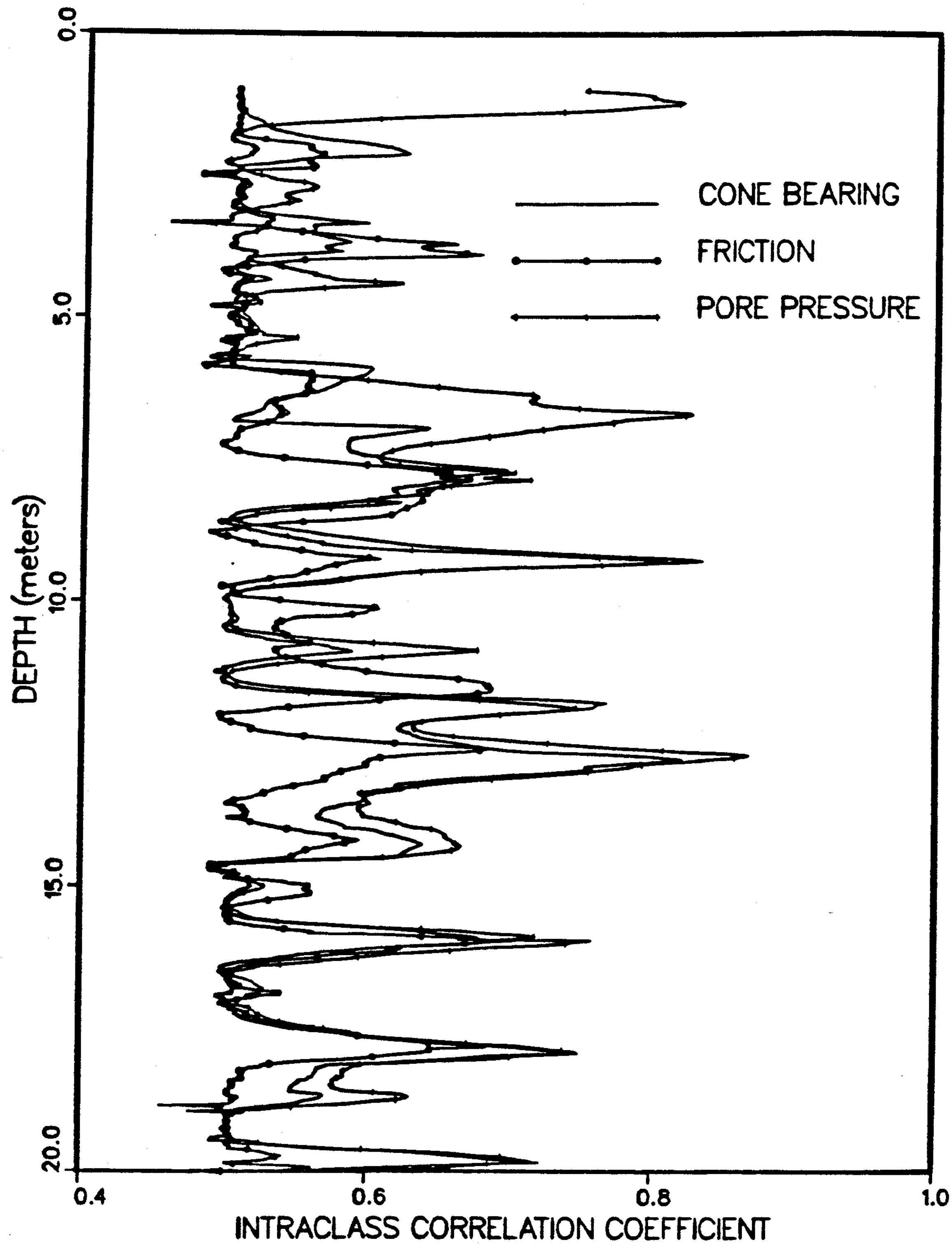

Figure 10 : Intraclass Correlation Coefficient for Cone Bearing, Friction and Pore Pressure at Haney Site for a Window Width of 2.0 meters.

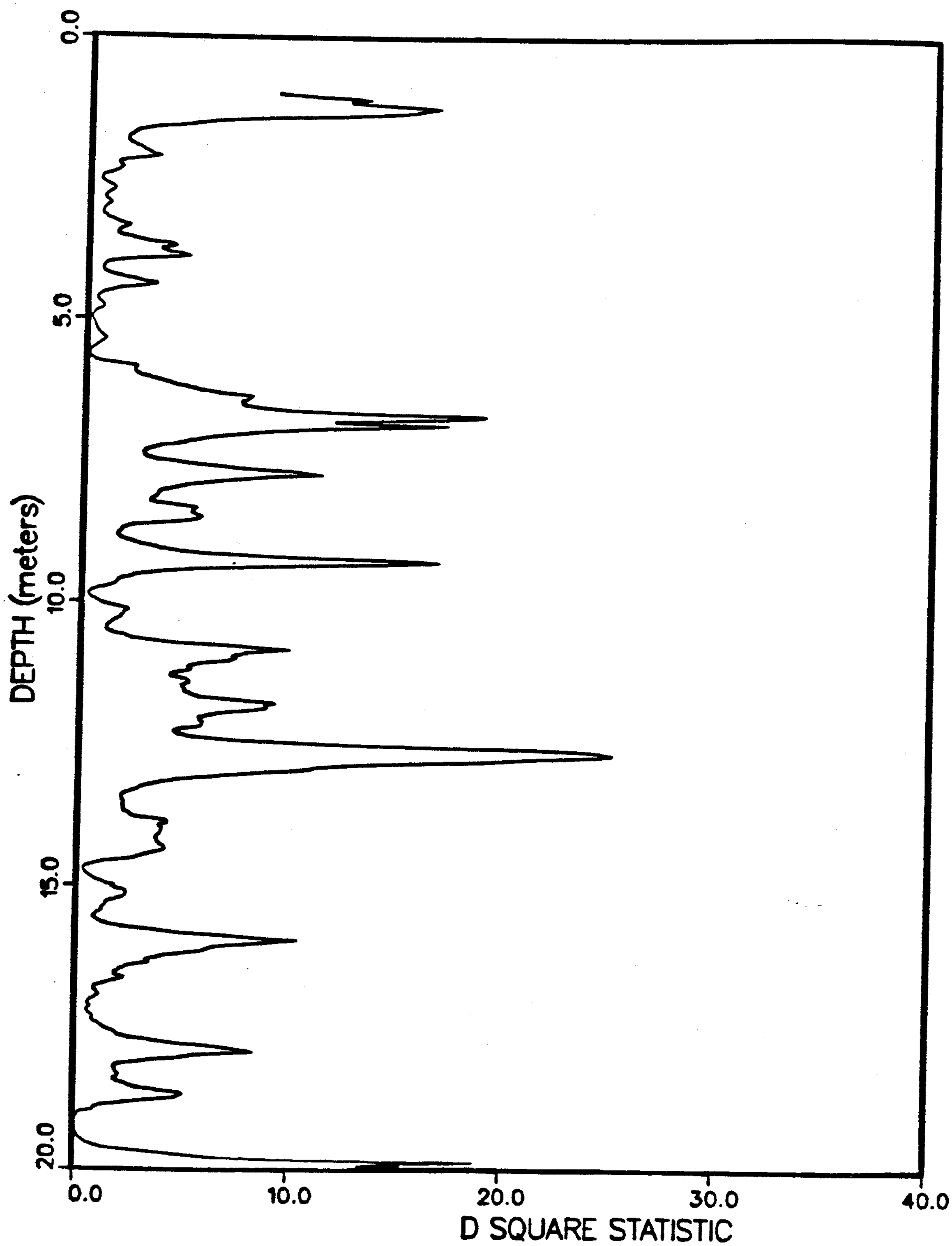

Figure 11 : D^2 Statistic of Multivariate Analysis at Haney Site for a Window Width of 2.0 meters.