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Modelling soil stratification and classification from piezocone data

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The piezocone (CPTU) has become one of the most popular site characterisation tools used by geotechnical engineers. Although limited by the hardness of the profile to be penetrated, the piezocone is unrivalled in its ability to define the in-situ seepage regime and is the only available routine technique, other than continuous sampling, that provides a continuous profile of soil stratification below the water table. In addition, piezocone data can be analysed empirically or theoretically to give soil parameters and direct correlations for geotechnical design. This paper demonstrates a numerical procedure for analysing piezocone data for the purposes of stratification and classification. The procedure employs polynomial curve fitting techniques to identify the principal layers of the profile, which are then refined and classified according to the classification chart proposed by Jones and Rust (1982). The procedure is evaluated against a field profile from continuous sampling and is shown to give an accurate representation of sub-surface stratigraphy with the advantages of speed, cost and operator independence.

INTRODUCTION

The usual progression of geotechnical site investigation with the piezocone is to perform soundings, develop detailed site profiles, and then derive the necessary parameters or correlations required for design. If necessary, selective sampling and testing may be used to provide site specific calibrations. For an in-depth description of piezocone equipment and standard test procedures, reference can be made to Lunne *et al* (1997) and De Beer *et al* (1988). Considerable experience exists in determining the nature of the subsurface stratigraphy (ie the extent, thickness and location of different soil layers) from piezocone data: Baligh *et al* (1980), Jones and Rust (1983), Olsen and Farr (1986), Robertson (1990), Jefferies and Davies (1991), Vreugdenhil *et al* (1994), and many more.

Modern-day testing equipment allows for electronic data acquisition and generates large amounts of data, even for a single sounding. Although computer software greatly facilitates the handling and visualisation of data, stratification is usually a laborious hands-on process involving an experienced geotechnical engineer familiar with interpretation techniques. The procedure proposed in this paper provides a numerical alternative for profiling piezocone data based on trigonometric polynomial curve fitting (Vermeulen 1994; Vermeulen & Rust 1995), supported by the classification system developed by Jones and Rust (1982; 1983). The procedure can readily be programmed into a standard spreadsheet utility to automate the whole process. The final results require minimal input from the engineer to confirm the profile, or to make minor alterations if necessary, thus significantly reducing time, cost and effort.

In summary, the numerical procedure regards the trends followed by trigonometric polynomials fitted to the cone resistance and pore pressure data respectively. Using these trends the profile is divided into a number of principal layers and classified using a stan-

dard soil classification system for the piezocone. If a more detailed stratification is required, for example identifying thin drainage layers within a greater clay stratum, the principal layers can be subdivided and classified using the soil classification system.

To evaluate the performance of the proposed new procedure, a numerically derived profile is compared with a profile from continuous sampling in close proximity to the piezocone sounding. It is shown that the numerical procedure is able to capture the main features of the profile, but is limited by the inherited limitations of the classification system used. However, as classification systems evolve, either in general or site specific, so will the accuracy of the final product.

SOIL CLASSIFICATION CHARTS FOR CPTU TESTS

The first attempt at soil identification with pore pressure measurements was published by Baligh *et al* (1980). They presented the results of cone penetration soundings (CPT) together with separate Wissa-type piezometer soundings in two sedimentary clay deposits (Wissa *et al* 1975; Torstensson 1975). The CPT gave cone resistance, q_c , and sleeve friction, f_s , values, whereas the piezometer probe provided pore pressure, u_t , information. The authors found the piezometer probe an excellent device for detecting thin permeable layers within the clay deposit, or conversely thin clay layers within sand, and suggested the development of a new device to measure both cone resistance and pore pressure simultaneously. Piezocone prototypes were subsequently developed concurrently by Torstensson (1982) and by Jones and Rust (1982).

Although commercial piezocone equipment is often fitted with a friction sleeve, it is now generally accepted that friction measurements are less accurate and reliable than cone resistance and pore pressure measure-

ments (Lunne *et al* 1986; Gillespie 1990). However, many authors still use friction sleeve readings as additional information for soil classification purposes.

Soil identification and classification charts using cone and pore pressure data from the piezocone have been developed by Jones and Rust (1982; 1983) (figure 1a), Senneset and Janbu (1985) and Senneset *et al* (1989) (figure 1b), Robertson *et al* (1986) and Robertson (1990) (figure 1c) as well as Jefferies and Davies (1991) (figure 1d). These charts are based on the observation that penetration through dense granular or stiff fine-grained soils produces relatively high cone resistances together with low or negative pore pressures, whereas the opposite is true in loose granular and soft clay soils. Classification systems make use of correction and normalisation procedures to account for the effects of the ambient pore pressure and in-situ stress state on the measured data – these are dealt with in the next section.

Although classification charts give familiar material-type descriptions, it should be noted that these classifications are indicative of the way in which the material behaves in response to the strains imposed by the advancing penetrometer. However, they are based on sound soil mechanics principles including hydraulic conductivity and its influence on pore pressure response, compressibility, etc, all of which are a function of soil type.

Identifying the interface between two different soil types using piezocone test data is complicated because the measurements are influenced by a finite volume of soil surrounding the sensor elements. The transition from one layer to another will not necessarily be sharply defined. Cavity expansion and strain path theories, supported by experimental studies, show that cone resistance is influenced by material ahead of and behind the penetrating cone (Treadwell 1975; Schmertmann 1978; Campanella & Robertson 1988). The size of this influ-

ence zone is dependent on the stiffness of the material and can be several cone diameters in extent. The result is that the cone will sense the change in material type before it has reached the next layer and will continue to sense the effects of the previous layer well into the next one. Pore pressure measurements, however, are far more responsive to layer changes and can theoretically be accurate down to 5 mm according to Lunne *et al* (1997).

NUMERICAL STRATIFICATION AND CLASSIFICATION

A trigonometric polynomial is the truncated or finite form of an infinite Fourier Series and consists of alternating sine and cosine terms and their coefficients. These polynomials are used in the proposed numerical procedure as a first order approximation to the principal

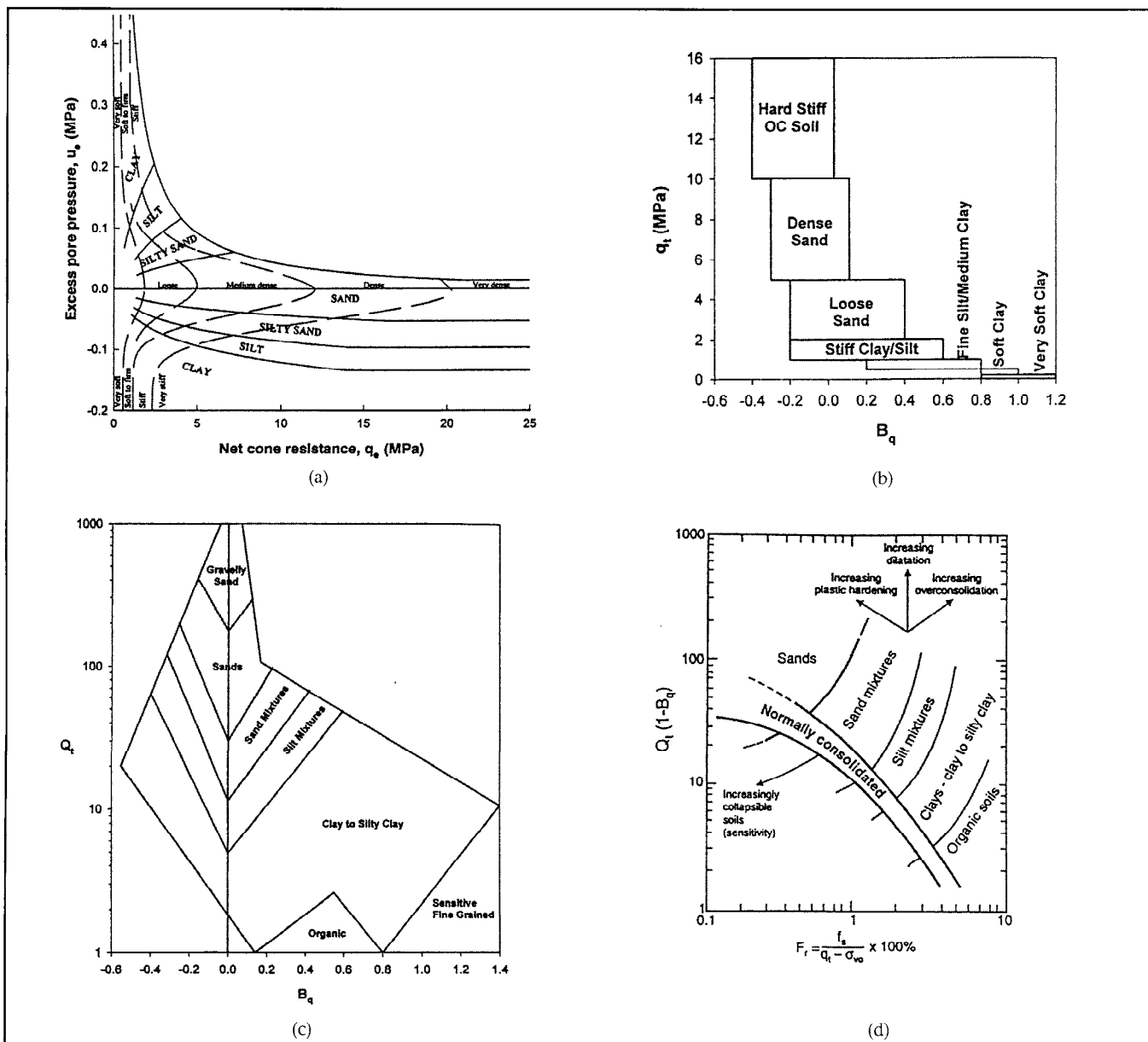


Figure 1 Soil behaviour type classification charts for the piezocone, after (a) Jones and Rust (1982), (b) Senneset et al (1989), (c) Robertson (1990) and (d) Jefferies and Davies (1991). Note: charts are valid for filter element placement behind the cone tip

stratification of a piezocone sounding. Once the raw field penetration data have been properly corrected and normalised, polynomials are fitted to the cone resistance and to the pore pressure plots. The accuracy of fit increases as the degree of polynomial increases. The purpose of the polynomials is to follow general trends in the profile as either the cone resistance or pore pressure responds to changes in material type and state. Possible layer boundaries are assumed to exist at the inflection points of these polynomials. Once the basic layering has thus been identified, it remains only to classify the layers using an existing classification system or chart. In many cases the profile obtained in this way should suffice for preliminary design, or where a rough estimate of the sub-surface stratigraphy is required. For a more detailed breakdown of layering and identification of specific features such as thin drainage seams, etc, the basic layering structure can be refined and classified using the piezocone classification system. In summary, the trigonometric polynomials are used to delineate the basic layer structure of the profile, and the classification system to refine layer boundaries, if necessary, and to identify or classify each layer.

Data preparation

Instrumentation-related corrections

Close inspection of field piezocone data usually reveals a small misalignment in depth between corresponding peak values of cone resistance and pore pressure. The offset results from both the physical separation between the cone tip and the filter element, and the fact that cone resistance is affected by a far greater zone of material ahead of and behind the tip. In most natural soils the problem is hardly relevant as the offset (typically < 20 mm) is insignificant in relation to the thickness of the layers. However, in highly layered deposits, such as tailings dams, the pore pressure offset can obscure valuable information. The phenomenon can best be resolved by lining up the pore pressure plot with the cone resistance plot to match, on average, peaks and troughs.

Cone resistance values must further be corrected for differential pore pressure effects resulting from unequal cross sectional areas on the cone face and behind the cone, where the pore pressure filter element resides (Baligh *et al* 1981; Campanella *et al* 1982). The net result is that water pressure alone will induce a residual cone resistance measurement as the cone face area, A_c , is larger than the area accessible to the water behind the cone face, A_g (figure 2). This effect is magnified if the cone resistance values are low and the generated pore pressures relatively high, such as in soft clays. The differential pore pressure effect is corrected in the following manner,

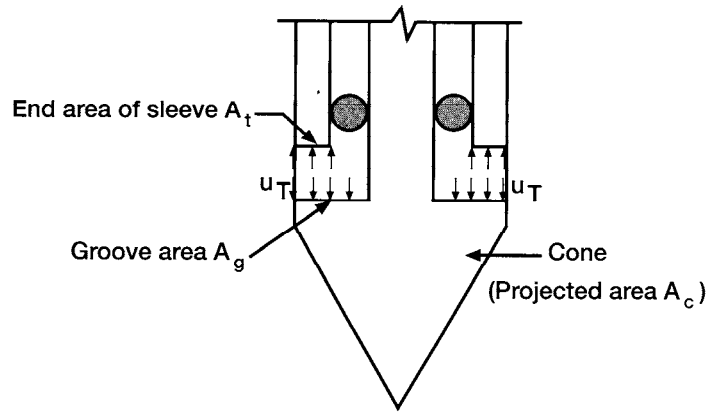


Figure 2 Differential pore pressure effect on unequal cone areas

$$q_t = q_c + \lambda \cdot u_t \quad (1)$$

where q_t = cone resistance corrected for unequal areas effect

q_c = measured cone resistance

u_t = measured pore pressure

λ = end area ratio, $\lambda = A_g/A_c$

A_g = area of the groove behind the cone tip

A_c = projected face area of the cone

$$u_e = u_t - u_o \quad (3)$$

where u_e = excess pore pressure

u_t = measured pore pressure

u_o = ambient pore pressure,

$\gamma'_w \cdot h$

γ'_w = apparent unit weight of water

The apparent unit weight of water, γ'_w , is a function of the level of the phreatic surface, the state of consolidation and the related seepage regime on location of the sounding.

In his 1984 Rankine lecture, Wroth stated that geotechnical relationships should be based on physical insight against a theoretical background and be expressed in a dimensionless form. In 1988 he suggested that cone penetrometer data be made non-dimensional, thus providing for relationships and classification systems that are directly comparable. Cone resistance data is normalised by the effective overburden pressure at the depth of measurement and the pore pressure data by the excess cone resistance in the following way,

$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \quad (4)$$

and

$$B_q = \frac{u_e}{q_e} = \frac{u_t - u_o}{q_t - \sigma_{vo}} \quad (5)$$

where Q_t = normalised cone resistance

B_q = normalised pore pressure

σ'_{vo} = effective overburden pressure, $\sigma_{vo} - u_o$

u_o = ambient pore pressure

Regardless of the way in which data is normalised, any classification system can be used with the proposed numerical technique, as long as the data is presented in the correct format for the system selected. Figure 3 shows the effects of data preparation and normalisation on a piezocone sounding, PZ8, from the Haiphong Export Processing Zone in Vietnam (Stuart 1993). The site is located on the Red River delta stretching 150 km in a north-south direction approximately 100 km inland. The deltaic deposits are of Quaternary age and comprise largely fine-grained silts and clays but with sands and fine gravels present. Shells occur

Interpretation-related adjustments

The corrected cone resistance values, q_t , can now be used to calculate the excess cone resistance, q_e , which is the resistance to penetration over and above the in-situ total stress at the depth of measurement. Excess cone resistance is a measure of the soil response normalised with respect to depth. Ideally the mean total in-situ stress should be used to normalise the excess cone resistance, which is influenced by the vertical overburden pressure and to an even greater extent by horizontal earth pressures (Jamiolkowski & Robertson 1988). In the absence of lateral earth pressure data, it has become standard practice to use only the vertical total overburden pressure to calculate the excess cone resistance. Therefore,

$$q_e = q_t - \sigma_{vo} \quad (2)$$

where q_e = excess cone resistance

q_t = cone resistance corrected for unequal areas effect

σ_{vo} = total vertical overburden pressure

above the water table

$\sigma_{vo} = \gamma_{nat} \cdot h$ and

below the water

table $\sigma_{vo} = \gamma_{sat} \cdot h$

γ_{nat} = average

natural unit weight

of the material

γ_{sat} = average saturated

unit weight of the material

h = depth of measurement

Similarly the excess pore pressure or pore pressure generated by the advancing penetrometer is obtained by subtracting the ambient pore pressure from the recorded pore pressure.

frequently and also, less frequently, organically rich clays. Site investigations were carried out with piezocone testing, continuous tube sampling, core drilling and laboratory testing of selected undisturbed samples. Appendix A includes the soil profile from continuous tube sampling and testing in borehole DS2, next to piezocone sounding PZ8. The water table at the site is approximately 1 m deep with the saturated unit weight, $\gamma_{sat} = 18,2 \text{ kN/m}^3$. According to piezocone dissipation tests the pore pressure build-up is virtually hydrostatic with $\gamma'_w = 9,88 \text{ kN/m}^3$. The reasons for selecting this specific site were:

- the availability of both piezocone and continuous sampling records in close vicinity to each other
- the fact that the profile contains a good combination of different soil types
- the high level of the water table at the site – most piezocone classification systems were developed for saturated conditions only. (See figure 3.)

The effect of overburden pressure and ambient pore pressure is most evident in figure 3 for the uniform soft clay layer between 10 and 24 m. The raw data in figure 3a show a gradual increase in both penetration resistance and pore pressure, consistent with the strength increase with depth in a normally consolidated homogeneous clay layer. The normalised data in figures 3b and 3c shows virtually constant excess cone resistance in this uniform layer, representative of a single material type.

Trigonometric polynomial approximation

Trigonometric polynomial approximation provides a method for the least-squares approximation and interpolation of large amounts of data when the data are given at equally spaced intervals. This promises to be an effective way of analysing piezocone data, where it is not uncommon to be faced with 10 000 or more data sets in a single profile.

Trigonometric polynomials of degree n can be used to approximate $2m$ paired data sets $\{(x_j, y_j)\}_{j=0}^{2m-1}$

with the independent variable, x_j , equally partitioning the closed interval $[-\pi, \pi]$. The relevant equations are

$$S_n(x) = \frac{a_0}{2} + a_n \cos(n.x) + \sum_{k=1}^{n-1} [a_k \cos(k.x) + b_k \sin(k.x)] \quad (6)$$

with

$$a_k = \frac{1}{m} \sum_{j=0}^{2m-1} y_j \cos(k.x_j) \quad \text{for each } k = 0, 1, \dots, n \quad (7)$$

$$b_k = \frac{1}{m} \sum_{j=0}^{2m-1} y_j \sin(k.x_j) \quad \text{for each } k = 1, 2, \dots, n-1 \quad (8)$$

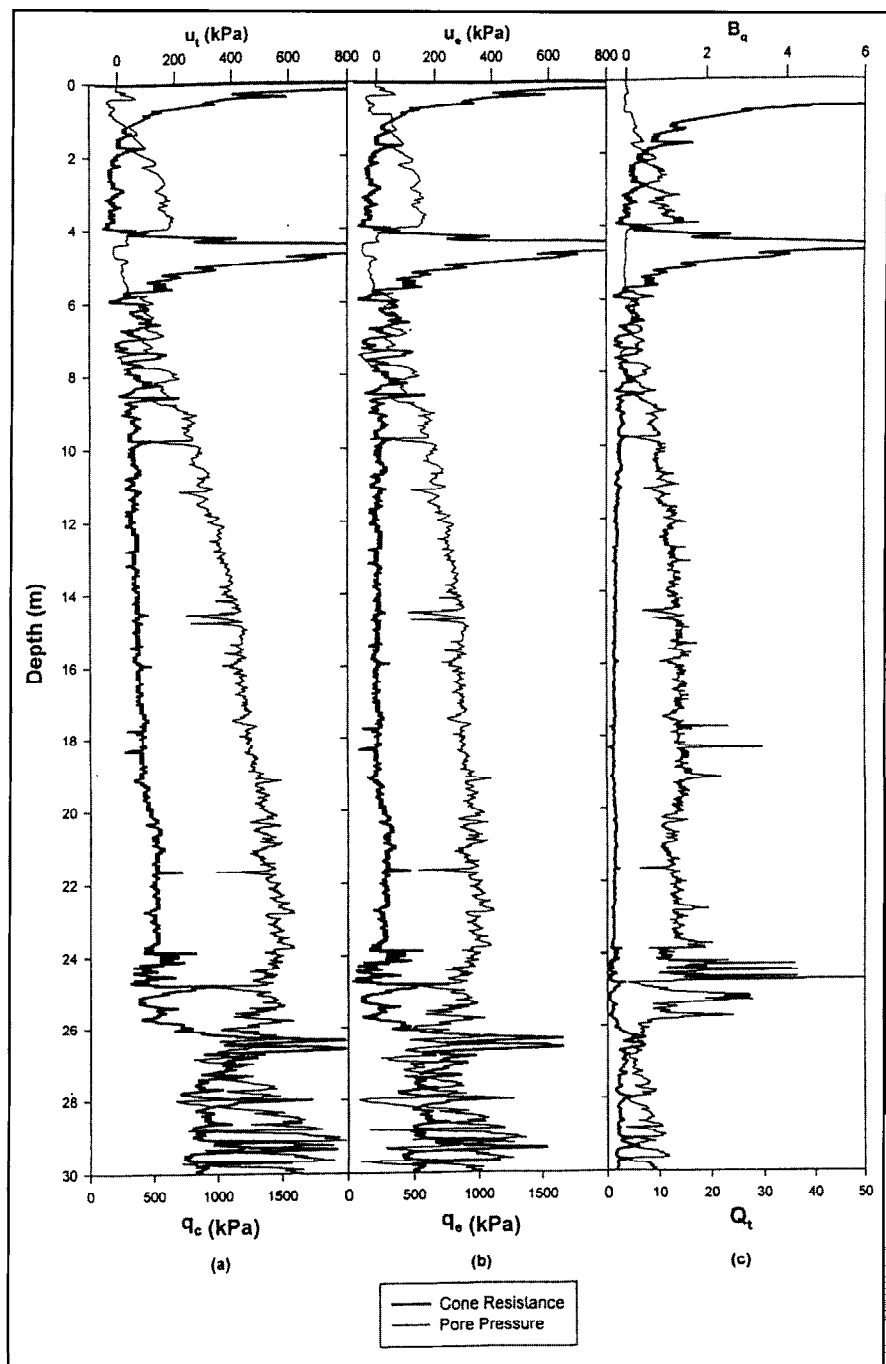


Figure 3 Effects of data preparation on PZ8: (a) raw field data, (b) adjusted to excess cone resistance, q_e , and excess pore pressure, u_e , (c) normalised to Q_t and B_q

Trigonometric polynomials (S_n) can only be fitted to piezocone data provided that the independent variable, depth, is recorded at equally spaced intervals. Fortunately cone penetrometer data generally tend to be spaced at equal depth intervals as a result of the constant time rate with which measurements are taken and the near constant rate of penetration of the penetrometer (standardised at 20 mm/sec).

Trigonometric polynomial approximation can then be applied to piezocone test data in the following manner:

- $2m$ paired data sets: Paired data sets imply an even number of data sets; if there is an uneven number of data sets in a data file, the last set is simply duplicated.

- $\{(x_j, y_j)\}_{j=0}^{2m-1}$: Sounding depth

becomes the independent variable, x_j , and either excess cone resistance, q_e , or excess pore pressure, u_e , the dependent variables, y_j .

- x_j must partition the closed interval $[-\pi, \pi]$: The depth measurements, which range from zero to the depth of penetration, have to be transformed to the interval $[-\pi, \pi]$. A simple transformation,

$$z_j = -\pi + j \left(\frac{2\pi}{2m-1} \right) \quad \text{for each}$$

$j = 0, 1, \dots, 2m-1$, results in data of the form

$$\{(z_j, y_j(z))\}_{j=0}^{2m-1} \quad \text{over the interval}$$

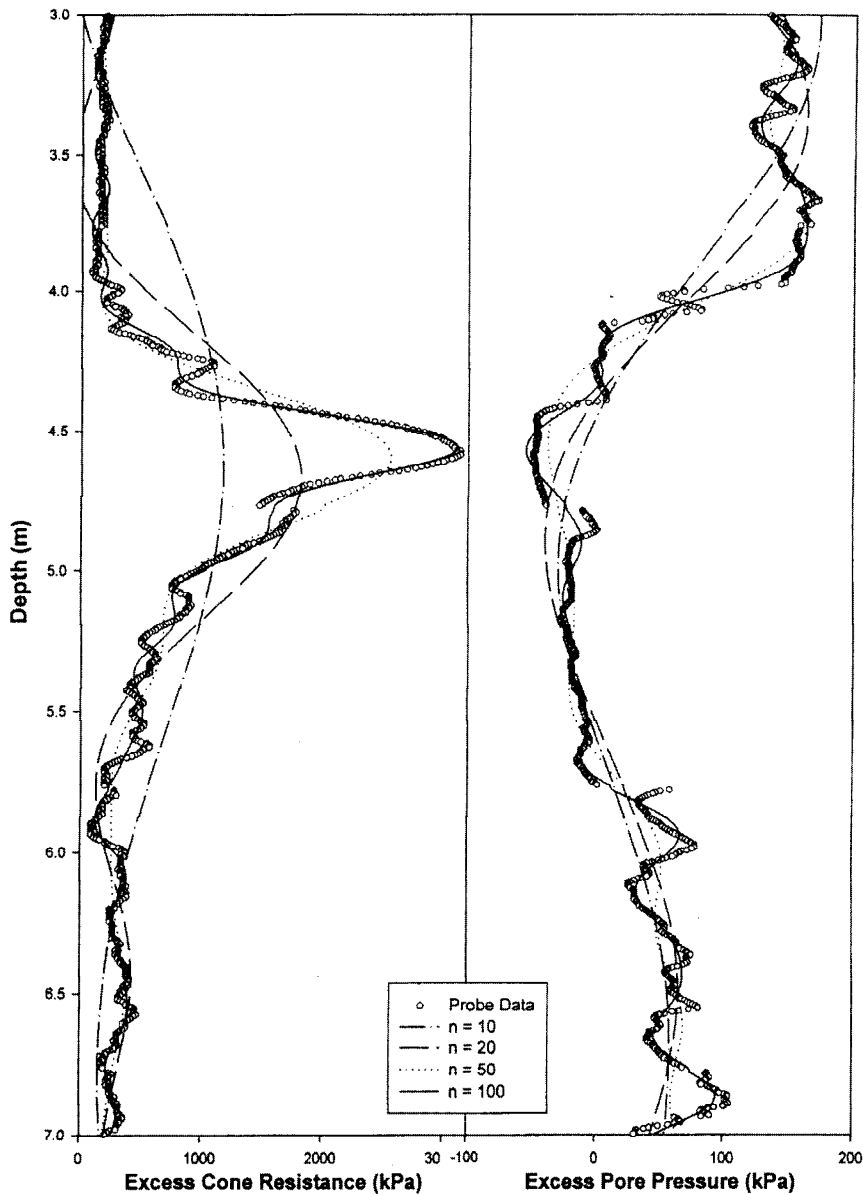


Figure 4a Fitting trigonometric polynomials of increasing degree to PZ8, detail showed of the depth increment between 3 m and 7 m

$[-\pi, \pi]$. This transformation spaces the cone resistance and pore pressure data at equal intervals over $[-\pi, \pi]$.

These assumptions together with equations 6, 7 and 8 can be applied to piezocone data, after the raw data have been normalised. Increasing the degree of fit, n , results in an increased accuracy of approximation. The optimum degree of fit depends on the complexity of the soil profile, the depth of the sounding and the purpose of the fit. For a shallow, simple stratigraphy, where only a rough guide to the layering is sought, a degree of $n = 5$ to 10 should suffice. On the other hand, for a deep, complex stratigraphy, where details are important, a degree of $n = 20$ to 100 may be needed. The degree of fit is determined by the analyst and provided the fitting procedure is computer programmed, it is only a matter of changing the n value, running the analysis and assessing the

results in graphical format. Figure 4a on page 6 illustrates fitting trigonometric polynomials of increasing degree to part of the piezocone sounding PZ8; note the closeness of fit achieved at $n = 100$ in figure 4b on page 7.

Stratification and classification

Once polynomials have been fitted to the cone and pore pressure data the profile can be stratified in the following manner. Inflection points on the polynomials are located by analysing slope changes. The slope of a polynomial changes sign at local maxima or minima, i.e. peaks and troughs that are located in the middle of major layers. The $n = 20$ polynomial shows this clearly for the slightly harder layer around 4,5 m in figure 4a. The interfaces between consecutive layers are then assumed to exist midway between the peaks and troughs. This results in sep-

arate stratifications of the profile according to cone resistance and pore pressure respectively, that are then combined to give the basic structure of the profile. Layer boundaries identified by polynomials, fitted to the cone resistance and pore pressure plots respectively, may not correspond perfectly for each layer. Where discrepancies exist, the classification system may be used to find the most probable location of the boundary based on material type behaviour.

After the principal layering has been identified using trigonometric polynomials, all that remains is to classify the layers using one of the classification systems available (figure 1). The classification system or chart can also be employed to refine the basic layers before proceeding with classification. To do this a basic layer is scanned on the identification chart and, based on material response, subdivided and classified. This technique can be used for example to 'hunt' for a thin sandy layer within an otherwise thick clay deposit and vice versa.

The Jones and Rust classification chart, figure 1a, was selected for use in this paper and applies to an instrument with the pore pressure filter element placed directly behind the cone tip that has become the standard for piezocones with a single filter element. The Jones and Rust system was selected for the following reasons:

- It identifies a wide range of soil behaviour types from sandy to clayey soils.
- In addition to soil type it gives an indication of the state or consistency of the soil, ranging from very soft to very stiff for fine-grained material and from very loose to very dense for coarse-grained material.
- Provision is made for both positive and negative excess pore pressures.
- It is defined in terms of variables (excess cone resistance and excess pore pressure) that allow for the effects of in-situ stress and ambient pore pressure.

However, in the original chart there is lack of definition near the origin of the axes, i.e. low cone resistance and pore pressure values. The author has subsequently revised and modified the chart by expanding the soil type boundaries in this area, figure 5a. In addition the excess cone resistance axis is represented on a log scale as suggested by Jones (1992) to give preference of area on the chart to low strength soils. Figure 5b shows the corrected data from PZ8 plotted onto the new chart and illustrates the advantage of stretching the cone resistance axis in the low strength region, as indicated by the spread of data in the *Very soft & sensitive CLAY* zone. This data would have been compressed into a very narrow line on the original chart (see figures 5a and 5b).

In order to apply the classification chart for classification purposes, represen-

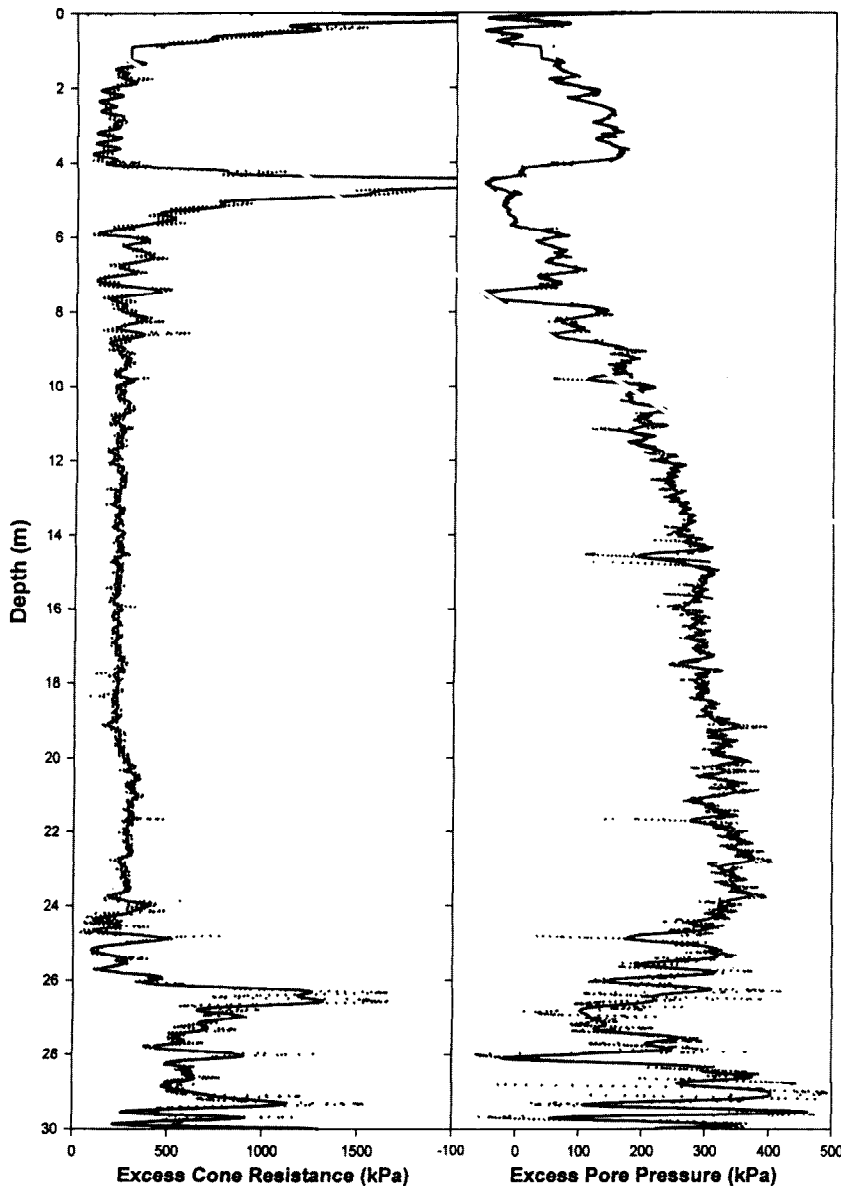


Figure 4b PZ8 fitted with a trigonometric polynomial of degree $n = 100$

tative values of excess cone resistance and excess pore pressure have to be calculated for each layer. This is done by calculating the average values over the mid third of each layer to capture the full response without including transitional effects from adjacent layers. Even then it is still possible to get an underestimate in thin layers of variable stiffness, where there is no opportunity for the measurements to develop their full potential. Based on simplified elastic theory, Vreugdenhil *et al* (1994), provided some insight as to how to correct cone resistance data in a thin stiff layer surrounded by soft soil. Using the relative thickness of the layer and surrounding soil they proposed a corrected cone resistance, q_c^* , as:

$$q_c^* = K_c \cdot q_c \quad (9)$$

where K_c = a correction factor as a function of layer thickness, H , in mm

$$K_c = 0,5 \left(\frac{H}{100} - 1,45 \right)^2 + 1$$

This correction should only be used if the layer thickness is 100 mm or less. Hence, slightly improved classifications can be achieved if the cone resistance is first corrected for layer thickness before applying the classification chart, especially for sand layers embedded in soft clay deposits that are often incorrectly classified as silty sands based on uncorrected data.

DISCUSSION

Figure 6 on page 8 shows the result of stratifying and classifying PZ8 using the proposed procedure ($n = 20$) and compares it with the continuous sampling profile from a nearby borehole DS2. The profile was prepared on a spreadsheet utility using programmable macro functions to

- prepare the raw data by adjusting the pore pressure offset and correcting for in-situ stress as well as ambient

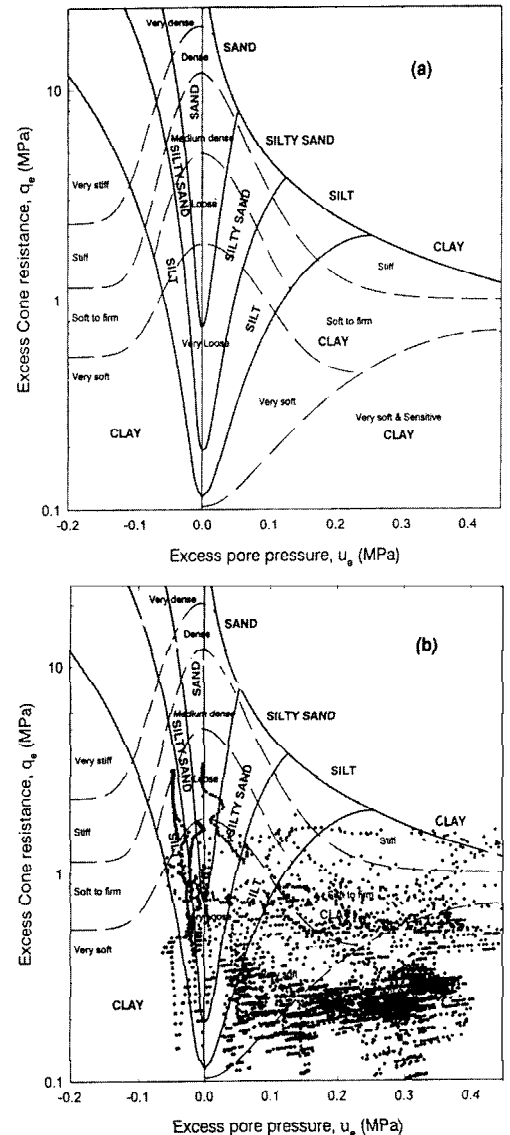


Figure 5a The modified Jones and Rust soil behaviour type classification chart
Figure 5b With corrected piezocone data from PZ8

pore pressure effects

- fit trigonometric polynomials of degree $n = 20$
- infer layers between inflection points in the curves and calculate average values of cone resistance and pore pressure over the mid third of each layer
- classify and simplify using the modified version of the Jones and Rust classification system.

The numerically derived soil profile compares well with the continuous sampling profile considering that the sampling profile is based on physical classification tests, while the piezocone profile was derived from indirect measurements of soil behaviour with the piezocone. A slight misalignment is evident in the location of the medium-dense sand layer between the borehole log and the piezocone sounding. This is believed to be the result of horizontal variation in the actual depth

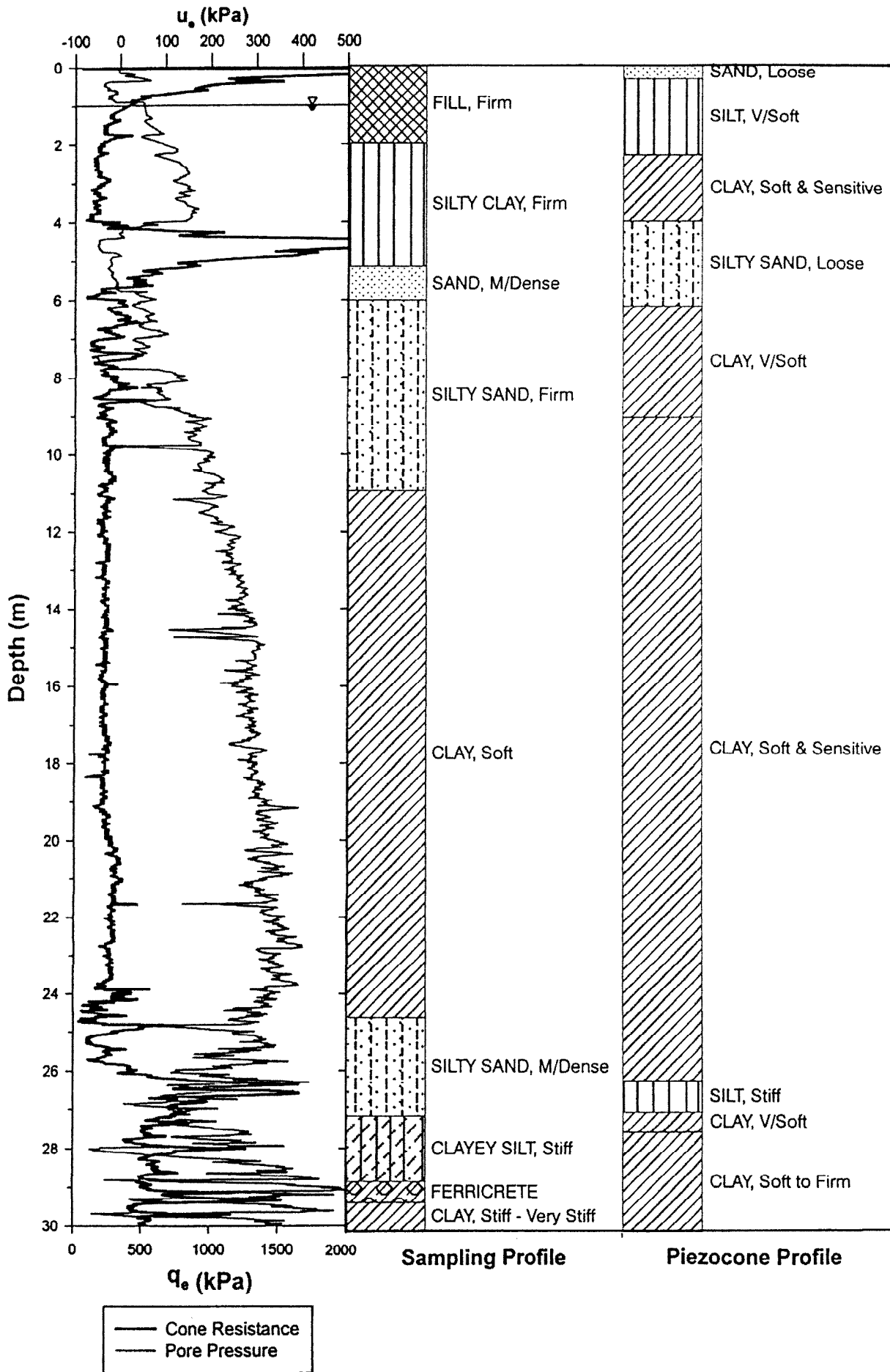


Figure 6 Piezocone profile of PZ8 compared with the profile from continuous sampling in the nearby borehole DS2

of this layer between the locations of the piezocone sounding and the sampling borehole. Based on the excess cone resistance plot between 4 and 6 m it appears that the full cone resistance might not have been mobilised in this relatively thin and dense layer surrounded by soft clay. However, correcting for the thin layer effect after Vreugdenhil *et al* (1994) still results in a *Silty Sand* classification from the chart. The explanation lies in the excess pore pressure response, which registered an average value of -20 kPa, indicating the presence of some fine material in the layer to support these pore pressures, hence *Silty Sand*. From a visual inspection of the q_c and u_e vs depth plots in figure 6 the soft homogeneous clay layer between 6 and 26 m shows up quite clearly. However, there appear to be some silty or sandy inclusions within the ranges of 6–10 m and 24–26 m, identified as *Silty Sand* layers in the sampling profile. These layers are picked up by the polynomials, but are lost on the soil classification chart. In these ranges the average excess cone resistance (± 250 kPa) is too low and the average excess pore pressure (100–250 kPa) too high to change the identification to that of a silty or sandy material. Only at a much smaller scale would layers such as the one at 24,8 m ($q_c = 700$ kPa, $u_e = 60$ kPa) be identified as silty material on the classification chart.

Although polynomial stratification of a profile is a purely mathematical and unbiased procedure, classification of the layers rely heavily on the classification system employed. A major advantage of the proposed procedure is that any classification system, or updated form of it, can be incorporated without any difficulties. The proposed numerical procedure, including polynomial stratification and layer classification, can potentially lead to major savings in cost and time on a large project. A good example would be to use preliminary piezocone soundings and exploratory borehole data to calibrate a classification system for local conditions. All subsequent piezocone data can then be reduced to soil profiles, rapidly and accurately.

SUMMARY AND CONCLUSIONS

The piezocone has gained a lot of popularity in South Africa as an in-situ site characterisation tool, especially in providing fast, reliable profiles of subsoil conditions. To complement the speed and versatility of the piezocone, a numerical procedure has been proposed to stratify and classify soil profiles, using trigonometric polynomial curve fitting techniques together with a soil classification system developed for the piezocone, the Jones and Rust chart in this case. By implementing these procedures the engineer is able to get a fast and reliable description

of subsoil conditions in the form of soil type and state classes with depth.

To conclude:

- Trigonometric polynomials show considerable potential as a first-order approximation to the stratification of cone penetration data, provided that the data has been corrected for instrument- and interpretation- related effects. However, the envelope over which the cone penetrometer senses soil variation leads to some imprecision in locating soil interfaces.
- Classification of the final profile is highly dependent on the classification system selected. However, the proposed procedure is flexible in its ability to accommodate any soil classification system for the piezocone, and future modifications to these systems.
- The main advantage of the proposed numerical technique is the speed and convenience with which large amounts of piezocone data can be reduced to soil profiles. The procedure requires minimal input from the engineer or technician, thus significantly reducing time, cost and operator dependence.

References

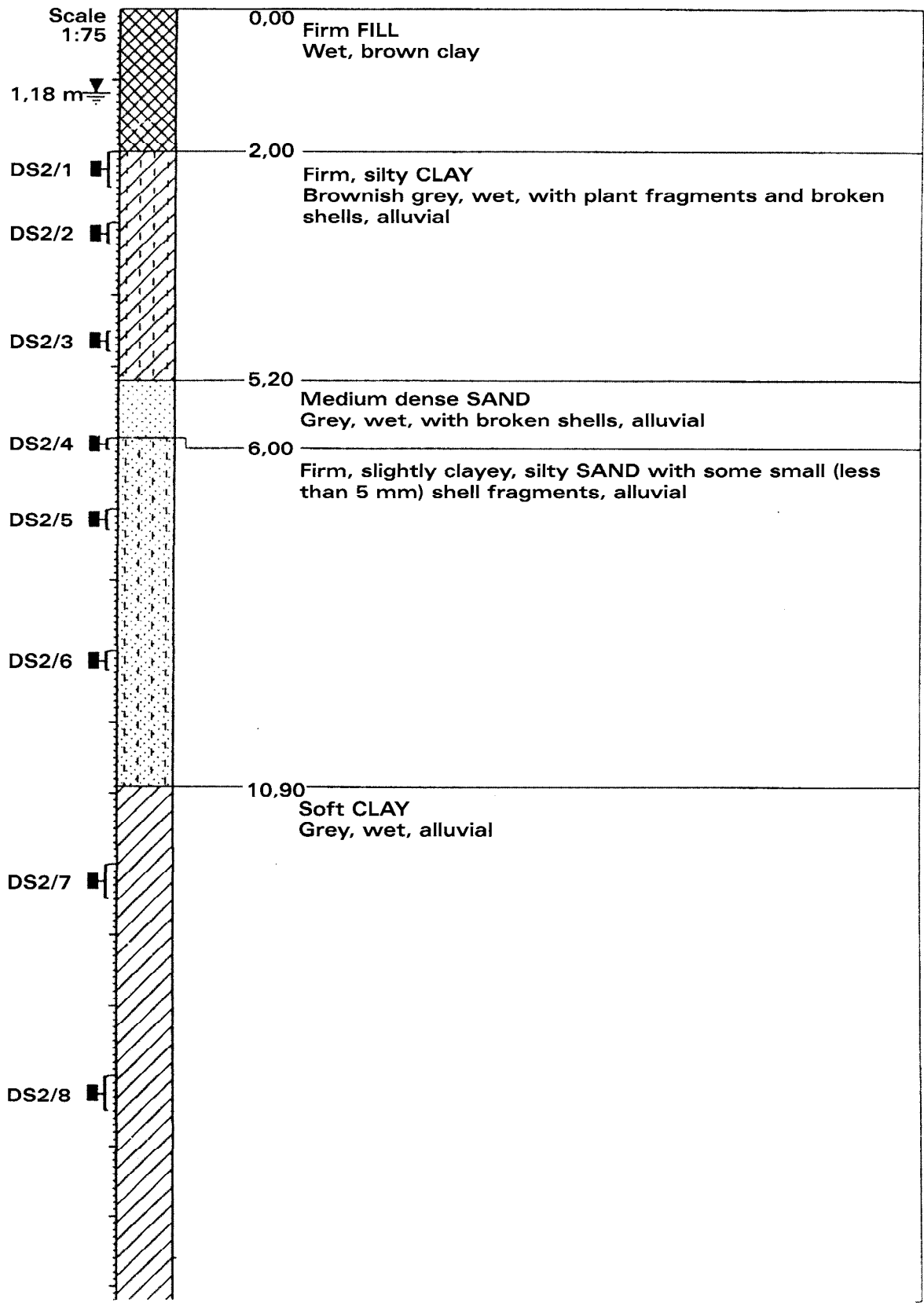
- Baligh, M M, Azzouz, A D, Wissa, A Z E, Martin, R T & Morrison, M H 1981. The piezocone penetrometer. Symposium on Cone Penetration Testing and Experience. ASCE, Geotechnical Engineering Division, St Louis, pp 247–263.
- Baligh, M M, Vivatrat, V & Ladd, C C 1980. Cone penetration in soil profiling. ASCE, *Journal of the Geotechnical Engineering Division*, 106(GT4):447–461.
- Campanella, R G & Robertson, P K 1988. Current status of the piezocone test. *Proceedings*, 1st International Symposium on Penetration Testing, ISOPT I, Orlando, vol 1:93–116.
- Campanella, R G, Gillespie, D & Robertson, P K 1982. Pore pressures during cone penetration testing. *Proceedings*, 2nd European Symposium on Penetration Testing, ESOPT II, Amsterdam, pp 507–512.
- De Beer, E E, Goelen, E, Heynen, W J & Joustra, K 1988. Cone penetration test (CPT): international reference test procedure. *Proceedings*, 1st International Symposium on Penetration Testing, ISOPT I, Orlando, vol 1:27–52.
- Gillespie, D G 1990. Evaluating velocity and pore pressure data from the cone penetration test. PhD thesis, University of British Columbia.
- Jamiolkowski, M & Robertson, P K 1988. Closing address: Future trends for penetration testing. Geotechnology Conference: Penetration Testing in the UK, Birmingham, pp 321–342.
- Jefferies, M G & Davies, M P 1991. Soil classification by the cone penetration test. Discussion. *Canadian Geotechnical Journal*, 28:173–176.
- Jones, G A & Rust, E 1982. Piezometer penetration testing CUPT. *Proceedings*, 2nd European Symposium on Penetration Testing, ESOPT II, Amsterdam, pp 607–614.
- Jones, G A & Rust, E 1983. Piezometer probe (CUPT) for subsoil identification. *Proceedings*, International Symposium, In-situ Testing, Paris, vol 2:303–398.
- Jones, G A 1992. Development of sounding equipment for the assessment of the time-settlement characteristics of recent alluvial deposits when subjected to embankment loads. PhD thesis, University of Natal.
- Lunne, T, Eidsmoen, T, Gillespie, D G & Howland, J D 1986. Laboratory and field evaluation of cone penetrometers. *Proceedings*, ASCE Speciality Conference, In-situ '86: Use of In-situ Testing in Geotechnical Engineering, Blacksburg, pp 714–729.
- Lunne, T, Robertson, P K & Powell, J J M 1997. Cone penetration testing in geotechnical practice. Blackie Academic and Professional.
- Olsen, R S & Farr, J V 1986. Site characterisation using the cone penetration test. *Proceedings*, ASCE Speciality Conference – Use of In-situ Testing in Geotechnical Engineering, Blacksburg, VA.
- Robertson P K, Campanella, R G, Gillespie, D & Grieg, J 1986. Use of the piezometer cone data. *Proceedings*, ASCE Speciality Conference, In-situ '86: Use of In-situ Testing in Geotechnical Engineering, Blacksburg, VA, pp 1263–1280.
- Robertson, P K 1990. Soil classification using the cone penetration test. *Canadian Geotechnical Journal*, 28:176–178.
- Rust, E 1993. Haiphong VGI City, Geotechnical investigation and preliminary evaluation of civil construction materials, Vietnam. Contract Report XV001P/01/93/11/1568, Van Niekerk, Kleyn and Edwards.
- Schmertmann, J H 1978. Guidelines for cone penetration test, performance and design. Federal Highway Administration, Report FHWA-TS-78-209, Washington.
- Senneset, K & Janbu, N 1985. *Shear strength parameters obtained from static cone penetration tests*. ASTM, Special Technical Publication STP 883, pp 41–54.
- Senneset, K, Sandven, R & Janbu, N 1989. Evaluation of soil parameters from piezocone tests. *Transportation Research Record*, 1235:24–37.
- Torstensson, B A 1975. Pore pressure sounding instrument. *Proceedings*, ASCE Speciality Conference on In-situ Measurement of Soil Properties, Raleigh, NC, vol 2:48–54.
- Torstensson, B A 1982. A combined pore pressure and point resistance probe. *Proceedings*, 2nd European Symposium on Penetrating Testing, ESOPT II, Amsterdam, vol 2:903–908.
- Treadwell, D D 1975. The influence of gravity, pre-stress, compressibility, and layering on soil resistance to static penetration. PhD dissertation, University of California, Berkeley.
- Vermeulen, N J 1994. CPTU profiling: a numerical method. MEng dissertation, University of Pretoria.
- Vermeulen, N J & Rust, E 1995. CPTU profiling: a numerical method. *Proceedings*, International Symposium on Cone Penetration Testing, CPT 95, Linköping, vol 2:343–350.
- Vreugdenhil, R, Davis, R & Berrill, J 1994. Interpretation of cone penetration results in multi-layered soils. *International Journal of Numerical and Analytical Methods in Geomechanics*, 18(9):585–599.
- Wissa, A E Z, Martin, R T & Garlanger, J E 1975. The piezometer probe. *Proceedings*, ASCE Speciality Conference on In-situ Measurement of Soil Properties, Raleigh, NC, vol 1:536–545.
- Wroth, C P 1984. The interpretation of in-situ soil tests. 24th Rankine lecture. *Géotechnique*, 34(4):449–489.
- Wroth, C P 1988. Penetration testing – a more rigorous approach to interpretation. *Proceedings*, International Symposium on Penetration Testing, ISOPT I, Orlando, vol 1:303–311.

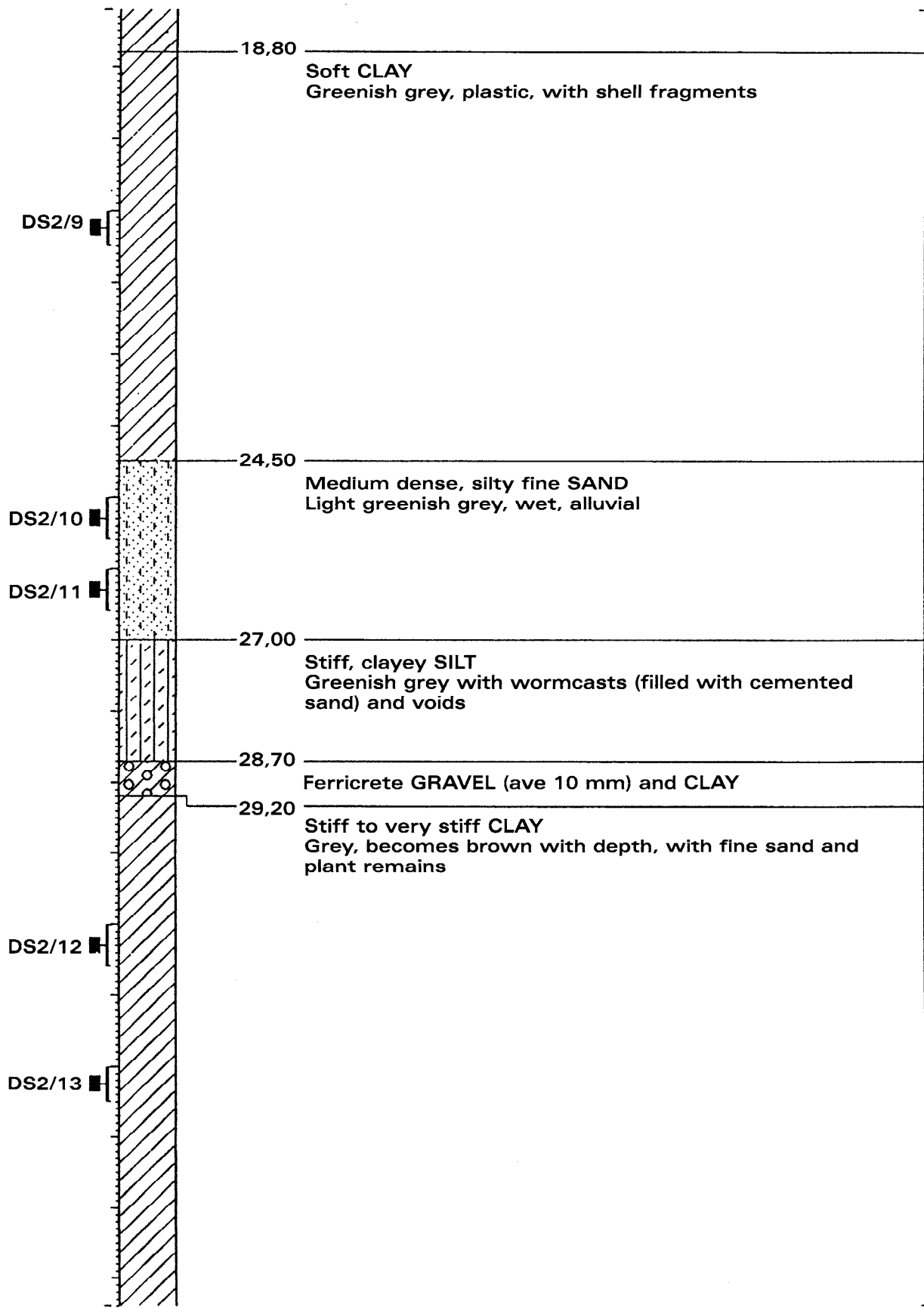
APPENDIX A

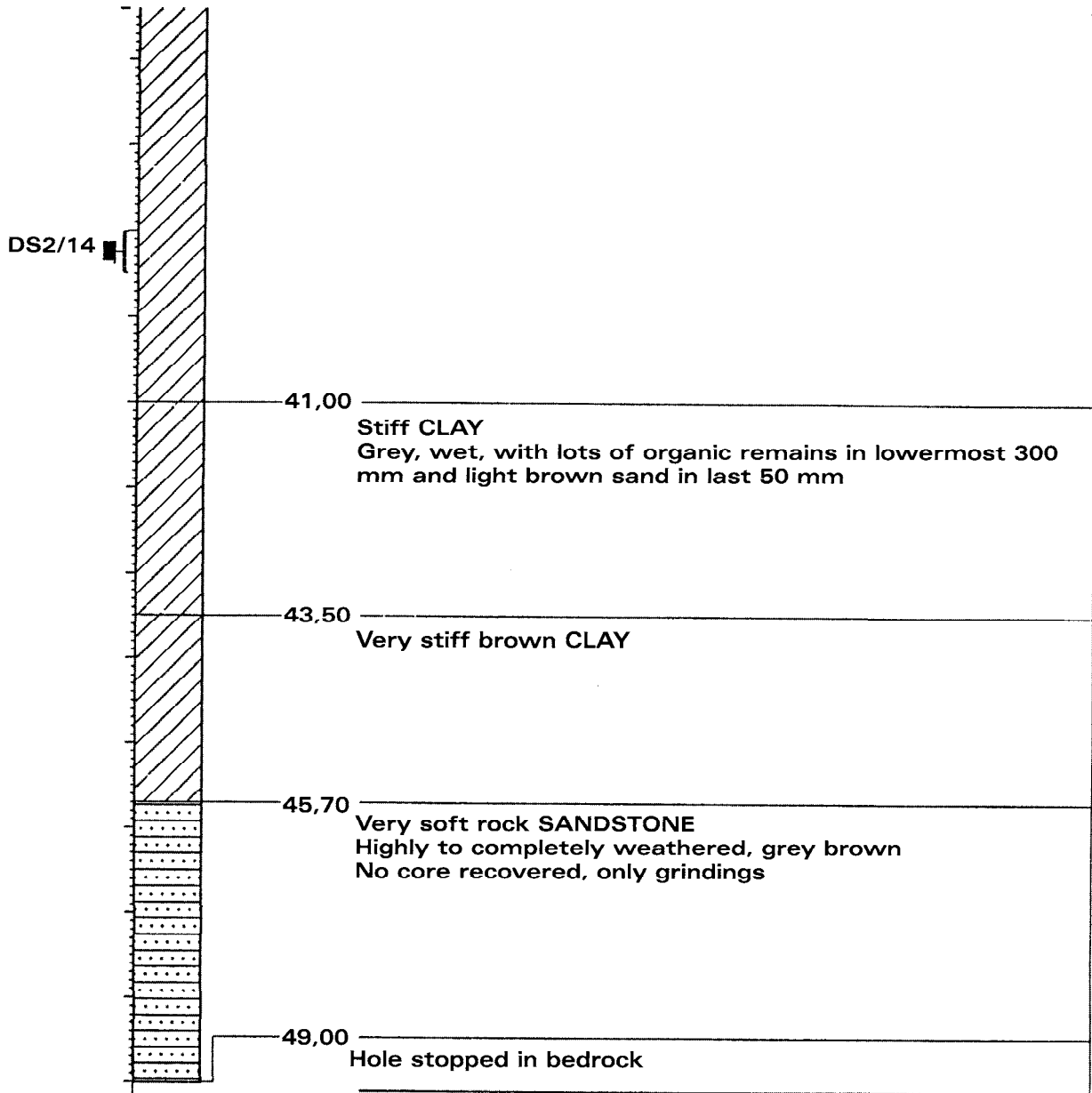
**BOREHOLE LOG
HAIPONG EPZ**

**HOLE NO DS2
Sheet 1 of 3**

JOB NUMBER: XV001P







NOTES

- 1 Undisturbed samples: DS2/1, DS2/2, DS2/3, DS2/4, DS2/5, DS2/6, DS2/7, DS2/8, DS2/9, DS2/10, DS2/11, DS2/12, DS2/13, DS2/14
- 2 Water table at 1,18 m
- 3 Drilling method: 0-45,7 continuous tube sampling
45,7+ tungsten double tube N size

CONTRACTOR : USC
 MACHINE :
 DRILLED BY :
 PROFILED BY : ajs
 TYPE SET BY :
 SETUP FILE : PROF-ENG.SET

INCLINATION :
 DIAM :
 DATE : 26 Sept 1993
 DATE : 03/12/93 15:07
 TEXT : A:\NHIPHONG.TXT

ELEVATION :
 X-COORD :
 Y-COORD :

HOLE No: DS2