Instrumented Borehole Drilling for Subsurface Investigation

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Abstract: The successful application of instrumented borehole drilling techniques in offshore exploration has encouraged its further use on-shore as a ground investigation tool. The drilling of holes for grouting tubes creates the potential for obtaining supplementary ground information, which may be valuable to the succeeding tunnel construction. The instrumented drilling system was therefore investigated to determine its power to discriminate between ground strata. The configuration of the drilling system in terms of plant, equipment, and testing procedures was standardized and applied at a site in Kennington Park in London. The general characteristics of the measured drilling parameters are given and qualitative and quantitative methods of interpreting the drilling parameters are demonstrated. The possible soil–machine interactions that are responsible for the measured drilling characteristics are examined. A new method of data interpretation is proposed for identifying soil formation changes. Previously published correlations and analyses of drilling were examined and tested by comparing the trend-lines of drilling data in London clay against known undrained strength data. The degree of correlation was found to be limited.

DOI: 10.1061/(ASCE)1090-0241(2002)128:4(283)

CE Database keywords: Boreholes; Drilling; Subsurface investigation; Gravel; Clay; Field tests.

Introduction

Instrumented borehole drilling arises from the observation that an experienced driller can develop a good ‘‘feel’’ for the nature of the materials being drilled. If the rig is instrumented and monitored by a computer, it should therefore be possible to establish an automatic expert system to derive soil properties through certain correlations. Drill holes can be used to obtain a general view of the soil formations prior to a detailed conventional investigation. Alternatively, a few conventional investigations are first carried out prior to carrying out further monitored drill holes. One motivation for the on-going development of the system is to capitalize on drilling data obtained from the drilling of grout tubes that are to be used for grouting works in tunnel construction and to refine the mode of operation ahead of ground variations (Buchet et al. 1999).

The concept of instrumented drilling has long been applied in the oil and gas industry (Somerton 1959), but it is still a comparatively new concept in on-shore geotechnical engineering. The first on-shore application was via a device called ENPASOL in the early 1970s (Hamelin et al. 1982). It is a system that is capable of recording various drilling parameters, such as bit torque, bit downthrust, and drilling speed. It is typically used on rotary destructive drilling rigs and can sometimes be of use on coring rigs. In the latter case, the main use is to complete the core description in case of poor recovery. Similar systems have been used in the past for soil/rock identification at dredging sites (Smith 1994) and in soil improvement projects (Pfister 1985; Pazuki and Doran 1995).

The paper will first give a brief description of the drilling system used and the drilling parameters measured in the field tests conducted at Kennington Park in London. Second, it will demonstrate the qualitative and quantitative methods of interpreting the drilling parameters. Finally, it will examine what may be learned about the drilling mechanisms in gravely sands such as Terrace gravel and in stiff clays such as London clay.

Equipment and Test Procedure

Drilling data varies with drilling equipment and the precise way it is used. Attempts to correlate soil information with drilling results using a mixture of types of drilling rig or drilling bits have been unsatisfactory. It is necessary to adopt a standardized method if correlations are to be made for use on other sites. The drilling rig used for the field tests at Kennington Park in London was of hydraulically operated rotary type for grout hole drilling (see Fig. 1). It has a 2.5 m long mast and a high-torque rotary drill head. API (American Petroleum Institute) rods of 90 mm diameter and a tricone bit of 113 mm diameter were adopted. A set of pressure transducers was placed at various locations of the hydraulic circuits of the machine in order to measure mud pressure, torque, downthrust, and holdback. The drilling rig was equipped with a real time data logger called ENPASOL-3 (developed by Soletanche-Bachy), which monitors, measures, and records the drilling parameters, producing a record at 5 mm intervals of the

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Note. Discussion open until September 1, 2002. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on March 28, 2000; approved on June 29, 2001. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 128, No. 4, April 1, 2002. ©ASCE, ISSN 1090-0241/2002/4-283–291/$8.00+$.50 per page.

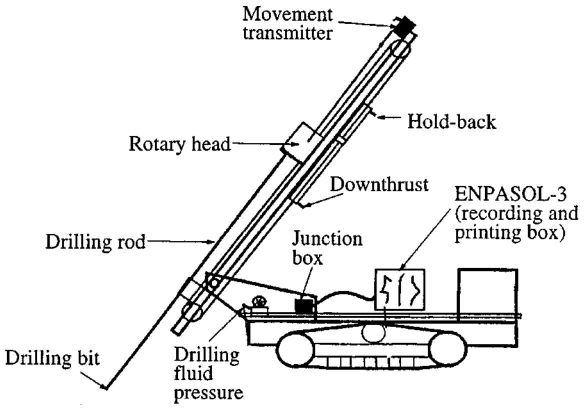


Fig. 1. Typical instrumented rotary drilling rig

characteristics of the formation being drilled. The stored data can be retrieved for further processing using the data management software JOE (Soletanche-Bachy 1999). Seven drilling parameters were recorded in the field tests as listed in Table 1.

Since the drilling method affects the data, an attempt was made to standardize the testing procedure. Throughout the drilling process a relatively constant drilling fluid flow rate, rotation speed, and thrust on bit must be provided in order to obtain consistent data. A relatively constant flow rate was provided to the borehole via a water pump that has a pumping head of at least 100 m. A constant and not very high rotation speed of 120 rpm was preferred because higher rates of advances could mask certain lithological variations that can be reflected by the torque parameter. A rotation speed of 200 rpm or less is thought to be acceptable (Girard 1985). Perhaps the most important control during the drilling is the down-thrust because for a given soil formation the drilling speed is roughly proportional to the down-thrust. Hence, to obtain consistent data, the net down-thrust was kept as constant as possible throughout the drilling process because for a given soil formation the drilling speed would increase with the increase of down-thrust. By cross-correlation statistical analysis of multiple adjacent boreholes data, it was found that the results obtained from the standardized tests performed at the Kennington site were more consistent than the nonstandardized tests performed at another site in London.

Table 1. Recorded Drilling Parameters

Parameters	Measured By	Tolerance	Note
Fluid pressure	Transducer (0-35 bars)	±3%	The pump normally provides a relatively constant hydraulic flow into the borehole. Ideally, pressure would be measured at the bit, but because of the impracticality of placing a transducer near the nozzle the pressure is measured adjacent to the pump at the ground surface.
Torque	Transducer (0-250 bars)	±3%	Torque is measured and applied to the drilling rod, and transmitted to the drilling bit, while aiming to keep a constant rotation speed.
Thrust on bit	Transducer 0-250 bars)	±3%	This is the main parameter that affects the drilling speed because for a given soil formation the drilling speed is roughly proportional to the down-thrust. Hence, to obtain information directly from the drilling speed, it is recommended that the down-thrust is kept as constant as possible during the drilling process.
Hold-back	Transducer (0-35 bars)	±3%	Holdback pressure is necessary to prevent the drilling rod from penetrating too fast, especially into a very soft ground, and to prevent the equipment falling into a hold when a cavity is encountered. In order to derive the effective net weight on the bid (W'), the holdback pressure has to be subtracted from the down-thrust, taking into consideration the self-weight of the rods.
Time	Internal clock (sec/5mm)	122 μsec	This is the time required to drill 5mm of soil. A movement transmitter sensor measures the distance of 5mm. This is important because the recorder is configured to record the drilling data at every 5mm of drilling.
Drilling speed	1/Time	<3%	It is the reciprocal of time and because of this reciprocation, it can be used as a "magnifying glass" when the time is very large. It is closely related to the 'hardness' of the strata being drilled when the down-thrust is kept reasonably constant.
Rotation speed	Electromagnetic proximity sensor	±3%	It is normally chosen to suit the drilling conditions, taking into account the type of drilling rig, and the wear and tear of the bit. A reasonably constant value of rotation speed should be used throughout the drilling process in order to obtain more consistent information from the drilling speed and torque measurement.

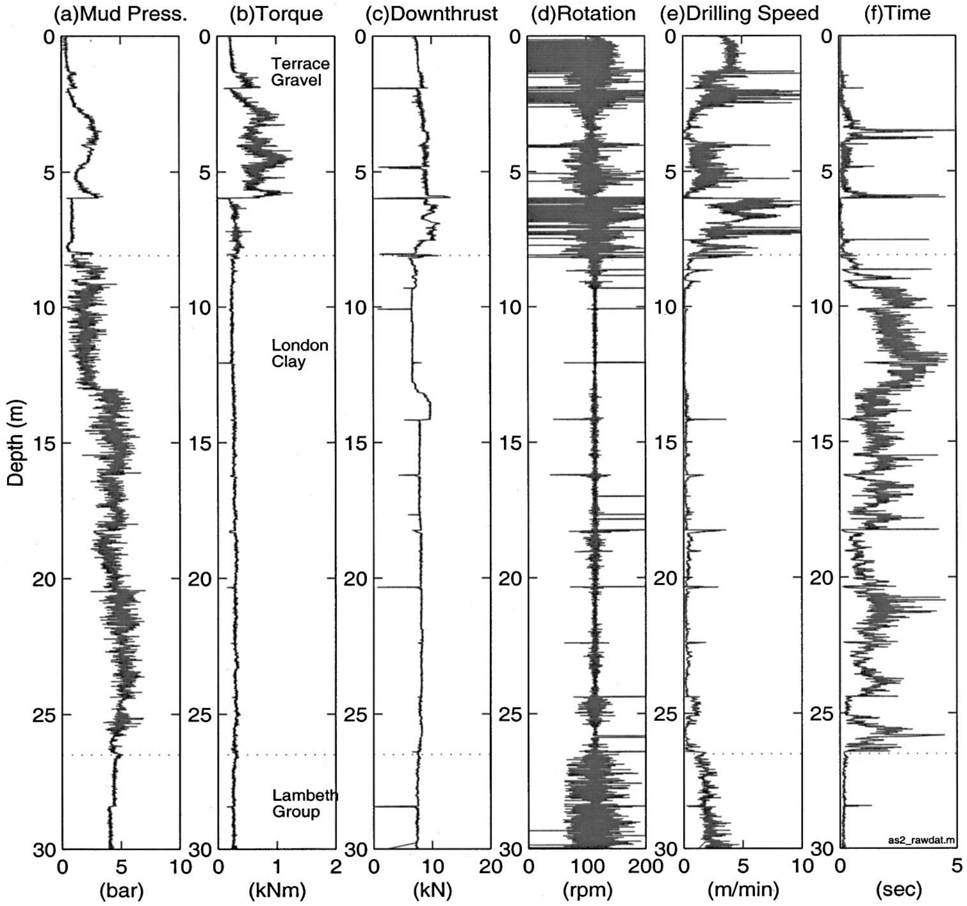


Fig. 2. Typical ENPASOL ''raw'' data (first 8 m was drilled with casing; soil layers shown were determined from rotary core samples)

Field Tests

The field tests performed at Kennington Park in London formed part of the ground investigation work for the risk assessment of the condition of existing old tunnel lining (Gourvenec et al. 1999). The ground investigation included rotary coring, self-boring expansion pressuremeters, self-boring load cells, self-boring permeameters, and vibrating-wire piezometers. The rotary coring and piezometer boreholes identified the sequence of deposits at the study area and groundwater was encountered at the top of the London clay stratum. Six instrumented drilling tests have been carried out on this site. All the tests were conducted using the same drilling rig and they were vertically drilled to a depth of 30 m, except for one test that extended to a depth of 50 m.

A typical output obtained from the instrumented drilling is plotted in Fig. 2, annotated with regard to the stratigraphy revealed in cores. The raw data obviously contained some noise. Nevertheless, the following characteristics can be observed.

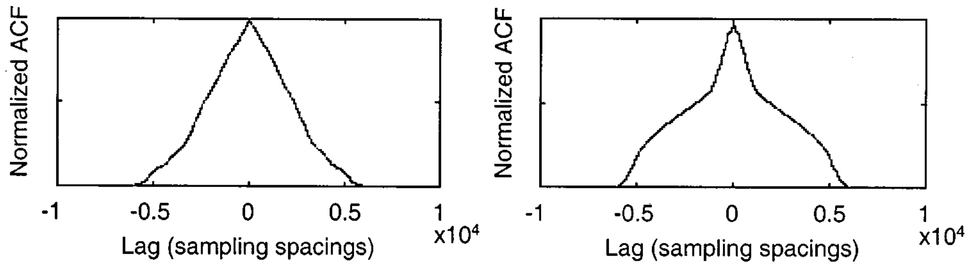
In Fig. 2(a), mud pressure in the sand and gravel layer (Terrace gravel) is much less noisy than in the clay layer (London clay), and generally has a lower average value, presumably because the bit is less likely to clog. In Fig. 2(b) we see a much higher and noisier torque encountered in the sand and gravel layer than in the clay layer, presumably attributable to bit resistance as large soil grains temporarily impede drilling advance while they are fragmented and ingested.

Fig. 2(c) shows that a reasonably constant net thrust was provided throughout the drilling process, as desired. It should be noted that the spikes (sudden drop of net thrust) observed in Fig. 2(c) coincided with rod changes. It took about 8 min to add a new rod to the rods already in the ground; during this period, because of the existence of the drilling fluid, the soil at the base of the drill hole would swell and soften. Thus, when drilling resumed, only a fraction of the previous down-thrust was required to push the rod further down.

A relatively constant rotation speed was also provided, as shown in Fig. 2(d), although the data was severely affected by noise, especially in the Terrace gravel layer and the Lambeth group (mixed layers of silty sands and clays). The signal contains two types of information: an average value and ''noise'' variations around the average value. As the magnitude of the observed noise seems to relate with soil formations, it is considered that the interaction between the drilling bits and the soil is contributing to the noise.

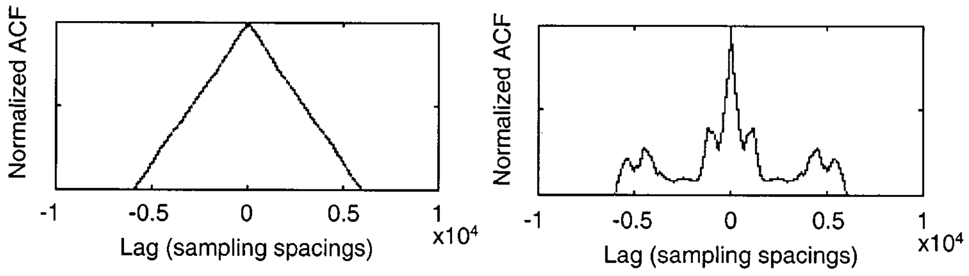
A higher average drilling speed was encountered in the sand and gravel layer than the clay layer, Fig. 2(e), and we may imagine that the tendency of the bit to clog with clay reduces its effectiveness as an excavation tool without increasing drilling torque. On the other hand, drilling speed was very noisy in the gravel, presumably due to the time taken to chip away particles too large otherwise for the bit to ingest. The time to drill 5 mm, Fig. 2(f), is the reciprocal of the average drilling speed over 5 mm, hence the longer it is, the harder the formation is to drill. The usefulness of the alternative measures of rate of advance can be appreciated simply by comparing Figs. 2(e and f).

It is striking that high and noisy torque with high and noisy drilling speed were indicative of the gravel, whereas high and



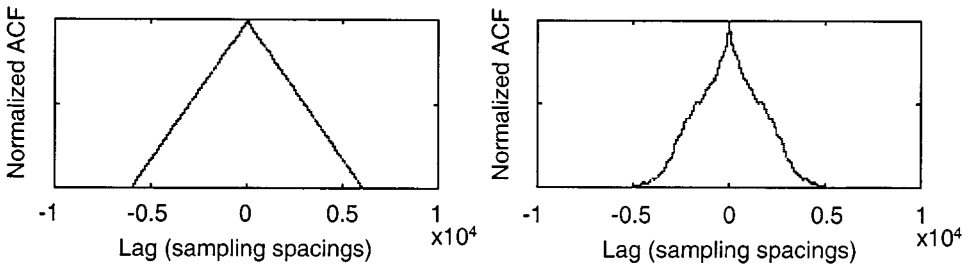
(a) Mud pressure
(Order of medium filter = 5)

(b) Torque
(Order of medium filter = 10)



(c) Net thrust
(Order of medium filter = 10)

(d) Drilling speed
(Order of medium filter = 25)



(e) Rotation
(Order of medium filter = 30)

(f) Time
(Order of medium filter = 25)

Fig. 3. Normalized autocorrelation function after filtering

noisy mud pressure with steady torque and low and steady drilling speed were indicative of the stiff clay.

Noise Filtering and Data Interpretation

It can be seen from the raw data (Fig. 2) that the data contains some "noise." As we have just observed, the noise seems to correlate with the ground properties encountered at the bit, it is not simply produced at random by the machinery. As a first step of data interpretation, filtering of white noise common throughout the record was performed on the signals before the usefulness of correlations using various combinations of drilling parameters against known variations in ground properties was assessed. This was achieved by carrying out a parametric study to determine the weight, order, and cutoff frequency for moving average, median, and Butterworth filters, respectively. The aim was to diminish a spike at zero lag in the autocorrelation function (ACF) (Denbigh, 1998). Similar but more extensive filtering and smoothing techniques and statistical analysis have been performed for CPT data (e.g., Vanmarcke 1977; Hegazy et al. 1996; Lunne et al. 1997; Fenton 1999).

A typical result, using the median filter on each of the drilling parameters together with the corresponding normalized ACF, is presented in Fig. 3. Each of the ACF quantities, normalized against its maximum value, is plotted against "lag" (sample spacing) in the figure. Since the depth data are equally spaced, we can infer depth, if desired, from the lag axis ($\text{depth} = \text{lag} \times 0.005\ \text{m}$). The signals of mud pressure, torque, down-thrust, and holdback required a low filtering order (5–10), indicating that they contain less outliers than the drilling speed, rotation speed, and time signals.

A triangular shape in the normalized ACF plots shows that when the lag increases (meaning two depth instants further apart), the two quantities remain perfectly correlated. The reason is that a constant signal of given duration (here 6,000 points) is regarded as being preceded and succeeded by zeros. When it is multiplied by the same signal with a lag, some of the extreme zeros cancel the original signal. This occurs increasingly until the lag equals the signal length. When the lag is zero, the autocorrelation is a maximum and just gives the variance in the reading.

A broad triangle like Fig. 3(c) would indicate that the downthrust has a reasonably constant value throughout the test since it was intended to be kept constant. Local effects, around the crest and towards the ends of the ACF triangles, have been observed in the torque parameter [Fig. 3(b)]. This is caused by different torque values in the Terrace gravel layer, London clay layer, and Lambeth group layer. The local effects are even greater in the

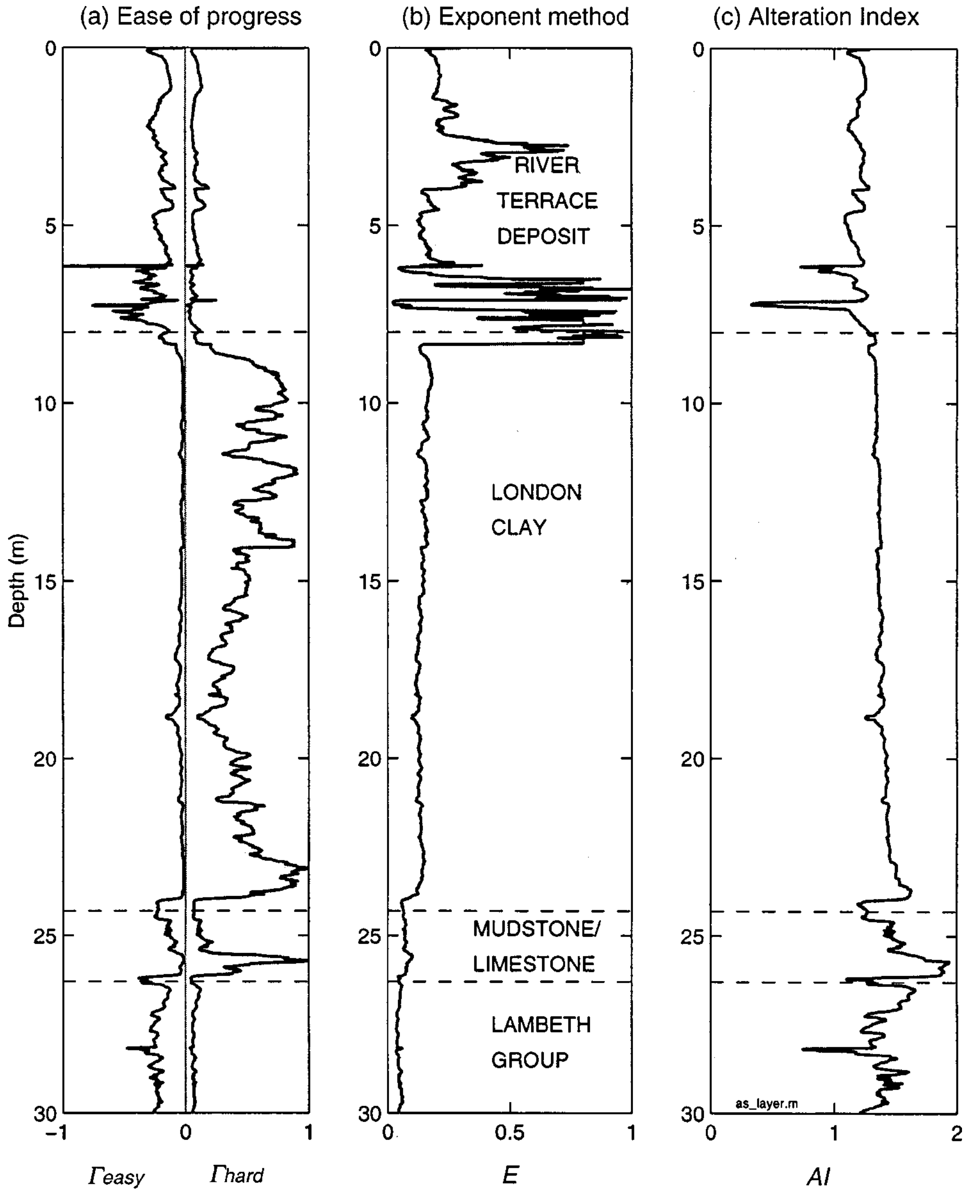


Fig. 4. Correlation between soil stratigraphy and combined parameters

drilling speed parameter, Fig. 3(d). The local effects indicate that there are three discernible ranges of drilling speed throughout the depth, as confirmed in Fig. 2(e). The mud pressure parameter also has a local effect but not as clearly defined as the torque and drilling speed parameters. The parameters with local effect can be used to identify soil layers.

Detection of Soil Formation Changes

Quantitative interpretation may be attempted using various combined parameters derived from a mixture of drilling parameters. Trial combinations may be selected either on an empirical basis alone or with some additional theoretical justification. For rotary drilling in rock it has been well recognized that the possible drilling mechanisms are crushing and chipping. It is, however, difficult to define a clear drilling mechanism in soil; so a theoretical formulation is presently in doubt. Therefore most of the combined parameters referred to below are simply dimensionally correct empirical formulations.

Since there is an attempt to keep net down-thrust W' and rotational speed ω_d constant in a drilling test, drilling speed V_d and torque T_q can best be used to try to distinguish soil formation changes. Dimensional analysis reveals that two corresponding dimensional groups are the velocity group Γ_v representing the ratio of vertical speed over circumferential speed of a tooth, and the force group Γ_f representing the ratio of vertical force over horizontal force acting on a tooth, where

$$\Gamma_v = V_d/(\omega_d D) \quad (1)$$

$$\Gamma_f = W'/(T_q/D) \quad (2)$$

where D=bit diameter.

The (unknown) relationship between these dimensionless groups should characterize the ground failure mechanism at the drill-tooth and be sensitive to soil type. A new ease-of-progress ratio Γ_{easy} (called “soft” by some ENPASOL users) can be derived.

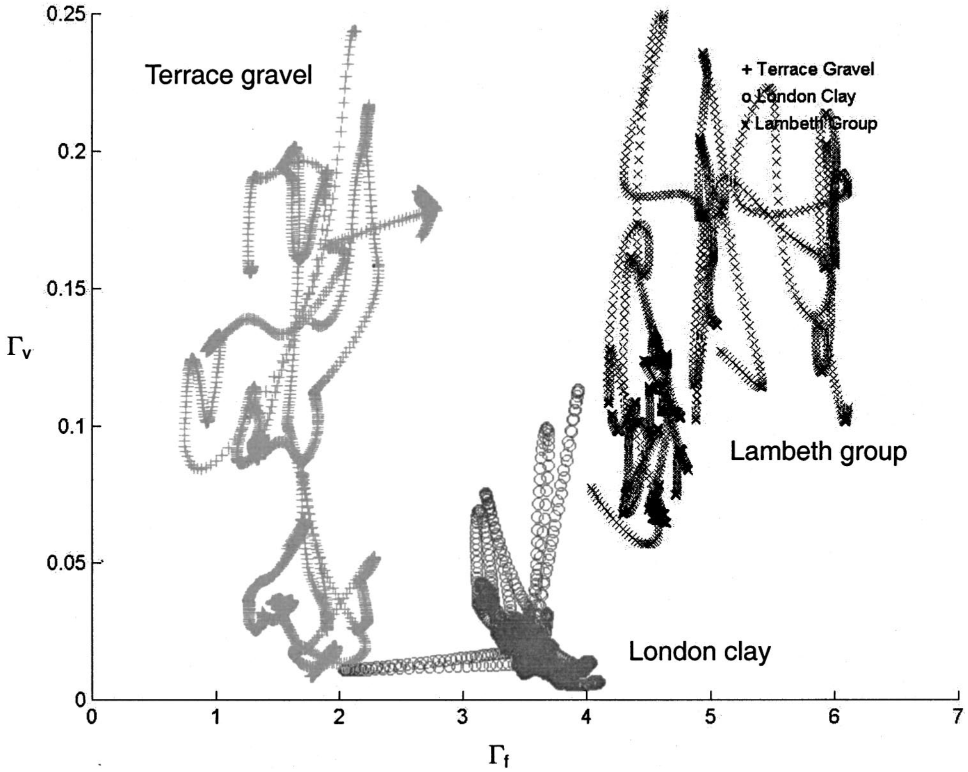


Fig. 5. Detection of soil formation using Γ_f and Γ_v

$$\Gamma_{\text{easy}} = -\Gamma_v/\Gamma_f = -\frac{V_d}{\omega_d \cdot D^2} \cdot \frac{T_q}{W'} \tag{3}$$

Since clays are difficult for progress, with a very small value of parameter Γ_{easy}, an inverse parameter Γ_{hard} (called "hard" by ENPASOL engineers) is used to capture variations:

$$\Gamma_{\text{hard}} = -\frac{1}{\Gamma_{\text{easy}}} \tag{4}$$

Γ_{hard} may be thought of as "hard to drill" and could relate to the difficulty of eroding and transporting soil particles away from the drill bit. In this way, any clay might tend to clog the bit and be found to be "hard" to drill, whereas sands may be "easy" to evacuate and quick to drill (the easy-to-progress method). As an example, the result of these empirical correlations for test ENP4 are presented in Fig. 4(a).

Jordan and Shirley (1978) proposed an empirical "d-exp" method to track the profile of rock strength in shales using only one dependent variable, i.e., drilling speed. However, their equation was dimensionally incorrect. By achieving dimensional consistency while retaining the form of the d-exp method, the supposed relationship between velocity ratio and force ratio is now a power curve (the E method):

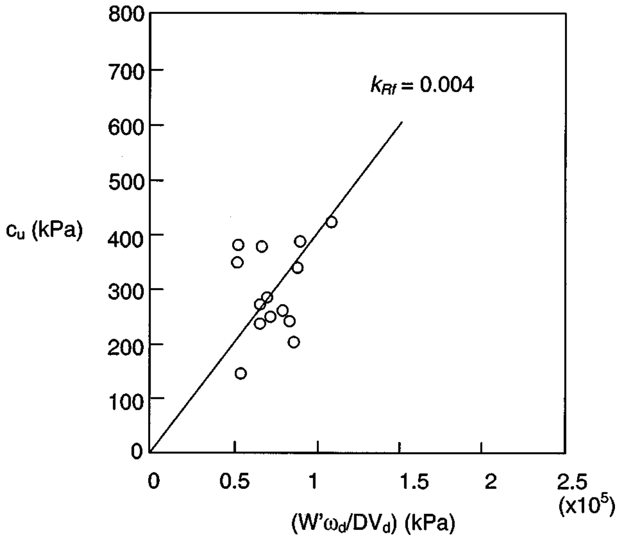


Fig. 6. Derivation of k_{R_f} for drilling resistance correlation

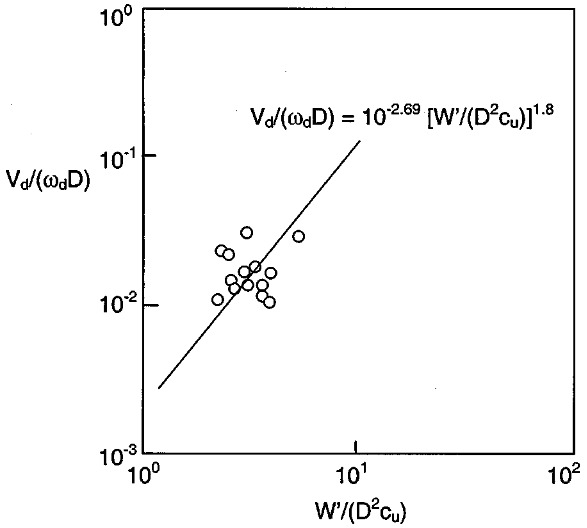


Fig. 7. Derivation of coefficients for Eq. (12)

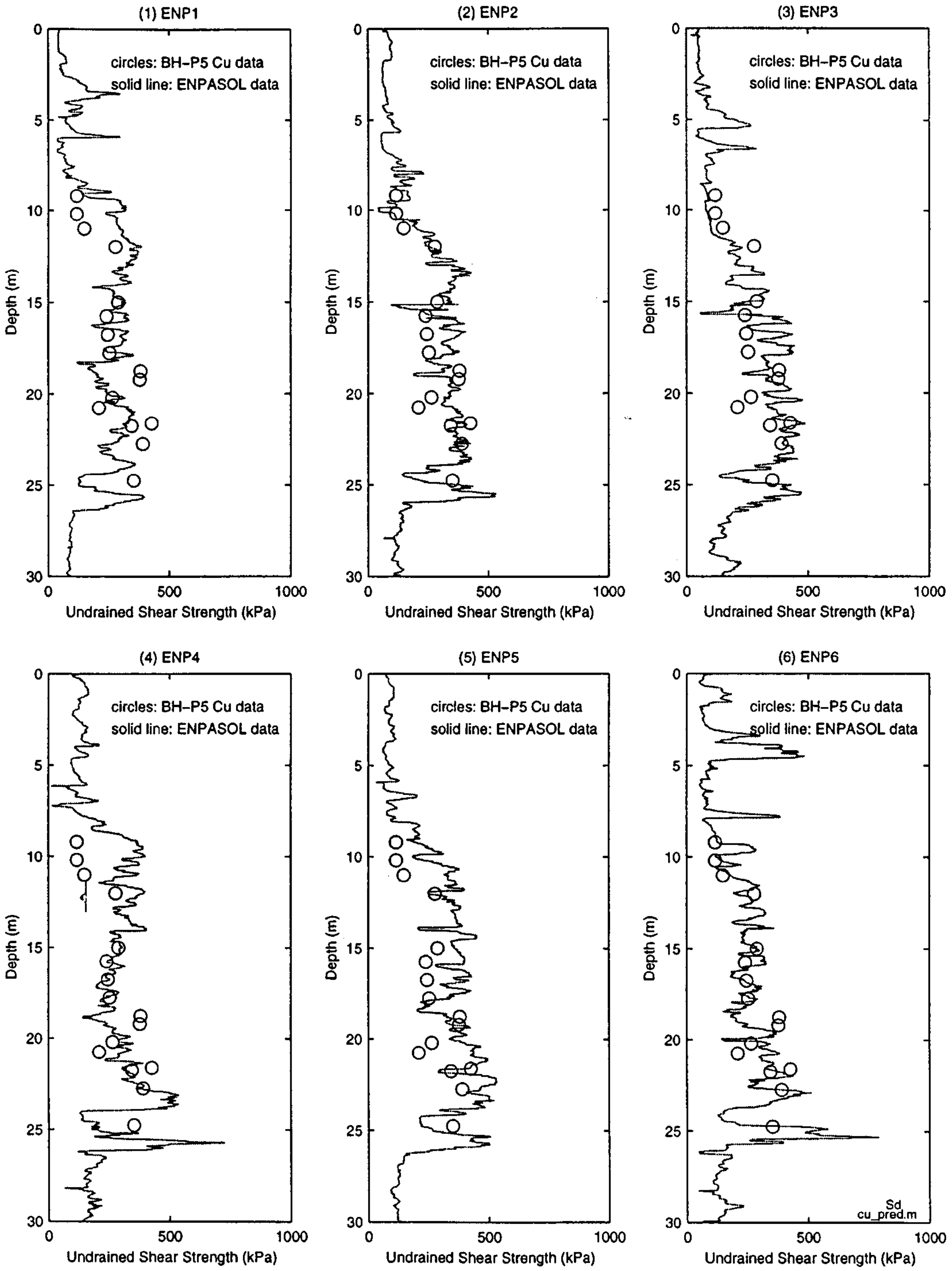


Fig. 8. Comparison between back-calculated c_u using Eq. (13) and laboratory measured c_u

$$E=\frac{\log\Gamma_v}{\log\Gamma_f}=\frac{\log\left(\dfrac{V_d}{\omega_d D}\right)}{\log\left(\dfrac{W'\cdot D}{T_q}\right)}\quad\text{or}\quad\Gamma_v=\Gamma_f^E \tag{5}$$

The result for test ENP4 using the E method is plotted in Fig. 4(b). We can see changes of E associated with soil formation changes. Unlike in London clay and the Lambeth group formations, the exponent E tends to fluctuate significantly in the Terrace gravel layer. This is the effect of the gravel causing a fluctuating torque, referred to earlier as another good indicator of the gravel formation.

Pfister (1985) proposed the alteration index:

$$\mathrm{AI}=1+\frac{W'}{W'_{\max}}-\frac{V_d}{V_{d\,\max}} \tag{6}$$

where $W'_{\max}$ and $V_{d\,\max}$ are the maximum effective weight on bit and maximum drilling speed, respectively. The value "1" is required simply for convenience so that AI is always a positive number. This index shows the possible variation of the drilling data with respect to the soil formation for a given borehole at a given site. AI varies from "0" in softer soil to "2" in the harder soil on a given site; and Pfister (1985) reported that AI was very sensitive in medium to low strength soils. The AI profiles for the Kennington test ENP4 are plotted in Fig. 4(c). Significant fluctuation of the AI profile is found in the Terrace gravel formation while approximately constant AI profile is found in the London clay formation. However, the discrimination is disappointing.

It can be seen that the combinations of dimensionless groups Γ_v and Γ_f used in both the ease-of-progress method and the E method indicated stratigraphic changes, obtained from the rotary and percussion coring boreholes, rather well. Of course, any relationship which exists between Γ_v and Γ_f will probably vary from ground type to ground type. Rather than selecting arbitrary functions such as Eqs. (3) and (5), it may be preferable simply to have a dimensionless plot of the velocity group Γ_v and the force group Γ_f. Fig. 5 maps data from all the drillings at Kennington park, focusing on three zones: Terrace gravel from depth 2.5 to 4.5 m, London clay from 17 to 21 m, and Lambeth group from 26.5 to 29.5 m. The regions inhabited by the data from the three distinct soil strata were, themselves, distinct. It is also useful that the noise experienced in the gravel appears as a Brownian process creating a diffuse zone for that material. The variation of Γ_v and Γ_f in the Lambeth group is related to the interlayers of very stiff clays and dense silty sands. It is arguable that Fig. 5 represents a clearer map of stratigraphy than any of the previous methods of characterization.

Correlation with Undrained Shear Strength

The relationship between combined parameters of drilling data and undrained shear strength c_u of the soil is examined. Values of c_u were taken from confined undrained triaxial tests performed on soil samples taken from an adjacent borehole.

Girard et al. (1986) examined the influence of each drilling parameter by keeping all the others constant. The drilling experiments were performed in artificial materials such as cement mortar and concrete of known strength characteristics. They found that drilling speed increased linearly with the increase of downthrust and rotation speed. However, drilling speed was inversely proportional to the unconfined compressive strength of the drilling material and the diameter of the drilling bit. Using these results, they proposed an empirical relationship to represent the ‘‘Drilling Resistance’’ R_f

$$R_f=\alpha_{R_f}\cdot\frac{W'\cdot\omega_d}{D\cdot V_d} \tag{7}$$

where α_{R_f} is a nondimensional coefficient of Drilling Resistance.

Drill teeth during a clean cutting operation should penetrate to a depth L proportional to V_d/ω_d, corresponding to the pitch of the ‘‘thread’’ being cut by a succession of teeth. The ratio of axial to tangential velocity sets the angle of the ‘‘thread,’’ and the circumferential spacing between teeth multiplied by the angle of the ‘‘thread’’ sets the penetration depth L of each tooth in relation to the cutting taken by its predecessor. Eq. (7) is the sort of expression one will derive by applying a constant strength to material of depth L being sheared ahead of each tooth. The weight on the bit is used as an index proportional to all the stresses.

If the undrained shear strength c_u were assumed to be proportional to R_f, we would have

$$c_u=k_{R_f}\cdot\frac{W'\cdot\omega_d}{D\cdot V_d} \tag{8}$$

The average value of k_{R_f} for the Kennington data has been found to be 0.004 as shown in Fig. 6. It must be recognized that Fig. 6 offers a very poor degree of correlation. It seems that one further data point might easily produce a quite different regression. It is as easy to believe that the combined drilling parameter R_f on the abscissa of Fig. 6 is generally uninfluenced by c_u on the ordinate as it is to believe that it is generally proportional.

Falconer et al. (1988) attempted to separate drilling bit effects from lithology effects by proposing the ‘‘Material Hardness’’ combined parameter. To derive the Material Hardness combined parameter, they assumed that the force per unit width of tooth F needed to push a sharp tooth into a rock is proportional to the maximum cross-sectional area embedded in the rock

$$F=\sigma_{\text{hardness}}\cdot L\cdot\tan(\theta) \tag{9}$$

where L is the penetration depth, σ_{hardness} is the *disturbed* material hardness, and θ is the tooth semiangle for roller cone bits, or the rake angle for the polycrystalline diamond compact (PDC) bits. They then conducted a series of single tooth tests but found that their assumption was only reasonable for ductile materials. Clearly their σ_{hardness} lumped together all the effects associated with cutting and did not account for the real material strength. Nonetheless, they assumed the maximum value of F to be on average proportional to W'/D, hence

$$\frac{W'}{D}=b_1\cdot\sigma_{\text{hardness}}\cdot L\cdot\tan(\theta) \tag{10}$$

where b_1 is a constant. Falconer et al. (1988) further assumed that the total penetration per radian of revolution V_d/ω_d divided by the bit diameter is proportional to $(L/D)^n$ where n is a number greater than 1, so

$$\frac{V_d}{\omega_d\cdot D}=b_2\left(\frac{L}{D}\right)^n \tag{11}$$

where b_2 is also a constant. Combining Eqs. (10) and (11) we can derive

$$\sigma_{\text{hardness}}=(b_3)^{1/n}\cdot\frac{W'}{D^2}\cdot\left(\frac{\omega_d\cdot D}{V_d}\right)^{1/n} \tag{12}$$

where $b_3=b_2/[b_1\cdot\tan(\theta)]^n$ and caters for all the relevant bit geometry factors. By using the power exponent n, Eq. (12) empirically extends the kinematic possibilities of bit action beyond the ‘‘thread’’ analogy used by Girard et al. (1986). Depending on circumstances, n might be taken as 1 if the teeth cut out a continuous chip of soil of depth L, rising to 2 if each tooth creates a noninteracting wedge shaped crater (Falconer et al. 1988). A similar equation was proposed by Somerton (1959).

For the purpose of soil drilling analysis, the material hardness σ_{hardness} might be compared with the undrained shear strength c_u. By substituting the drilling bit diameter D with 0.103 m in Eq. (12), the following regression can be obtained for the Kennington data (see Fig. 7):

$$c_u=0.31\cdot W'\cdot\sqrt[1.8]{\frac{\omega_d}{V_d}} \tag{13}$$

Once again, the degree of correlation is rather poor; and the same class of criticism can be made as was used regarding Drilling Resistance’s correlation. Using Eq. (13) with continuously recorded drilling data of W', ω_d, and V_d, the back-analyzed c_u for ENP1 to ENP6 can then be plotted together with the laboratory derived c_u as in Fig. 8. The correlation has been based around the mean, of course, so the result seems acceptable at first sight (ENP2, 3, and 6). However, measured c_u often goes up when Eq. (13) predicts that it should go down, inspect the ranges 10–12 m and 17–19 m of ENP1, 4, and 5 in Fig. 8.

The degree of match varied among six drilling data at the Kennington site and it can be argued that the local disagreements observed in some drilling tests are detecting the local heterogeneity of the ground. However, due to poor correlation between the undrained shear strength and the drilling parameters (Figs. 6 and 7) and complexity of the real nature [i.e., effect of local heterogeneity in relation to differences in sampling interval (1 m/sample for c_u and 5 mm/sample for the present data acquisition system)], unfortunately, no confidence can be placed on evaluating c_u from the drilling data at this site. Moreover, this negative result might have been expected when it is recalled that triaxial tests provide c_u against a failure criterion of ductile plasticity whereas the above analyses seem to be best related to tensile fracture. We have failed to show that the soil's undrained strength c_u is proportional to Drilling Resistance R_f or the *disturbed* material hardness σ_{hardness}.

Conclusions

A series of instrumented-borehole drillings has been conducted beneath Kennington Park, in London. ‘‘Noise ’’ in the raw data could be used to distinguish strata. In particular, sandy gravel made noise in both torque and speed whereas stiff plastic clay created noise in mud pressure. It is believed that these mechanisms are created by bit-soil interactions, jamming and clogging, respectively. In this sense ‘‘noise’’ is a paradoxical description of the variability of the data, since it can be used for ground characterization.

The present instrumented drilling method can be used in nearly every soil type for interpretation of soil formation changes while grout holes are being drilled. A dimensionless plot of the velocity group (Γ_v) versus the force group (Γ_f) in Fig. 5 exhibited some of the characteristic ‘‘noise’’ which was useful in recognizing gravel, as well as confirming the usefulness in site characterization of certain drilling parameters. Because of a relatively small sampling interval, it can offer to assess local variability of soil formation, which can sometimes be missed by conventional site assessment methods.

Previously published correlations and analyses of drilling were examined and tested by comparing the trend-lines of drilling data in London clay against known undrained strength data. In particular, correlations based on penetration mechanisms were investigated. Although the variation in ground properties was, perhaps, rather modest at the test site, the results were rather disappointing. The degree of match varied among six borehole data and the observed poor correlation may be related to the local soil heterogeneity effect against the sampling interval of different site investigation methods. It is, however, possible that the drilling mechanism in stiff clay should, like rock, be associated not with shear strength at all, but with tensile strength.

Acknowledgments

The writers are grateful to the European Commission who funded the above collaboration under the BRITE-EURAM III program. The permission of London Underground Limited to incorporate this research into their ground investigation work at Kennington Park is also acknowledged. The writers also acknowledge Mr. K. Isobe and Mr. Abe of Raito-Kogyo, and Mr. H. S. Teh for their participation in the preliminary stage of this study.

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