The use of the Mackintosh Probe for site investigation in soft soils

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Abstract

Dynamic probing can have an important role in geotechnical site investigation. The Mackintosh Probe is a lightweight and portable penetrometer. It is a considerably faster and cheaper tool than boring equipment especially when the depth of exploration is moderate and the soils under investigation are soft or loose. This paper presents the capabilities of the Mackintosh Probe for the investigation of soft deposits. A methodology for the use of the Mackintosh Probe is discussed and the repeatability of test results is studied. Correlations are developed between Mackintosh Probe results and those of the Standard Penetration Test (SPT), as well as, undrained shear strength (c_u). The study concludes that the application of the Mackintosh Probe for site investigation in soft deposits is appropriate and cost effective.

Keywords: Undrained shear strength, dynamic probing, Mackintosh Probe, repeatability, site investigation, standard penetration test

Dynamic probing is a continuous soil investigation technique, which is one of the simplest soil penetration tests. It basically consists of repeatedly driving a metal tipped probe into the ground using a drop weight of fixed mass and travel. Testing is carried out continuously from ground level to the final penetration depth. The continuous sounding profiles enable easy recognition of dissimilar layers and even thin strata by the observed variation in the penetration resistance. The Mackintosh Probe is a lightweight dynamic penetrometer and a considerably faster and cheaper tool than boring, particularly when the depth of exploration is moderate and the soils being investigated are soft or loose (Sabtan & Shehata 1994). The method can be used in difficult terrain such as swampy ground (Kong 1983). The purpose of this paper is to describe the capability and limitations of the Mackintosh Probe used for the study of engineering properties of recent soft deposits.

Mackintosh Probe

The Mackintosh Probe has been described by Clayton *et al*. (1995). It consists of a 27.94 mm diameter cone with a 30°-apex angle; 12.7 mm diameter solid rods and a 4.5 kg dead weight with standard drop height of 300 mm. It is a lightweight and highly portable tool (Fig. 1). The cone is advanced into the soil by standard blows from the drop weight and the number of blows for 100 mm penetration is counted (*M*). Friction losses on the rods are minimized through the use of enlarged conical couplings.

The Mackintosh Probe was developed for the investigation of peat and has been used in a variety of soft soils (Clayton *et al*. 1995). Chan & Chin (1972) and Kong (1983) have reported the use of the Machintosh Probe in the residual soils of Malaysia. These soils are derived from the disintegration and weathering of sedimentary rocks comprised mainly of siltstone and shale. Hossain & Ali (1988, 1990) have used the Mackintosh Probe in the sensitive clay of Obhor Sabkha in Saudi Arabia. The Sabkha sediments are predominantly composed of sand with occasional layers of clay, clayey silt, or silty clay, in addition to diagenetic salts that are formed *in situ*. Sabkha soil is a problematic soil due to its water sensitivity and chemical aggressiveness. The Mackintosh Probe has also been used in soft soil deposits in Iran (Shokrani 2000).

The main advantages of the Mackintosh Probe include:

(1) Speed of operation;
(2) Use in difficult terrain where access is poor;
(3) Minimal equipment and personnel are required;
(4) Equipment is very low cost;
(5) Simplicity of operation and data recording/analysis;
(6) Use in the interpolation of soil strata and properties between trial pits and boreholes;
(7) Reduces the number of boreholes required.

Experimental study

The data used in the paper were obtained from site investigations undertaken by the authors at three sites in the Khozestan province in the south of Iran. The sites were at the Emamie Port 140 km East of Mahshahr, Khamir Port 60 km East of Bandar-Abbas and Emam-Khomeini Port (Fig. 2). Geologically, the Khozestan plain is a continuation of the Saudi Arabian platform. This plain is covered by recent alluvium identified as clay, silt and some sand. These deposits are a product of the chemical and mechanical weathering of limestone, marl, sandstone, shale, and conglomerate (Souloki 1998). The terrain of this area comprises swamp due to

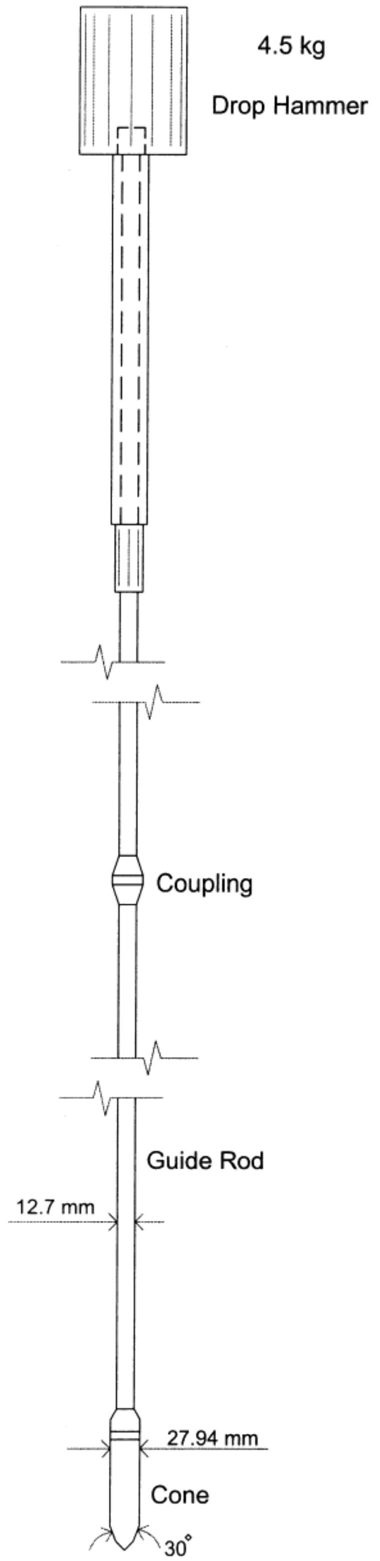

Fig. 1. The set-up and dimensions of Mackintosh Probe.

the high water level. The surface of the area is frequently covered with water during high tides, therefore the top soil has high water content and access is very poor.

In addition to dynamic probing, conventional boring and testing including hand-operated and borehole vane shear tests, UU triaxial tests on undisturbed samples in diameter of 35 mm and unconfined compression tests were undertaken at all three sites. The principal soil properties of these sites are given in Table 1. The soils investigated ranged from soft to medium clays with plasticity indices varying from 7 to 22.

In addition to the above-mentioned data, some published data by Sabtan & Shehata (1994) has been also considered for discussion.

Repeatability of Mackintosh Probe results

The repeatability of Mackintosh Probe results is an important consideration. To determine this a series of tests were carried out at each site. In each series, two, three, or four Mackintosh tests were repeated at very close proximity (in plan less than 0.5 m). Figure 3 shows the results of two series of tests undertaken at two locations at the Emamie site. A linear increase of M (blows/100 mm) versus depth can be seen for the top 1.0 m of soil. The results of repeat tests at the Khamir Port and Emam-Khomeini Port sites are shown in Figure. 4.

In order to study the repeatability of results it is important to choose a suitable parameter that represents the repeatability. The use of the standard deviation value (s) is not appropriate for this purpose because (s) is large for large values of M. However the coefficient of variation (C_v) can be considered as an indicative parameter because it represents a normalized standard deviation. C_v is calculated using the following formula:

$$C_v = s/\overline{x} \quad (1)$$

Where:

$\overline{x}$ is the average of M at each depth
s is the standard deviation of M at each depth

Table 2 shows some soil properties, determined by various standard tests, together with their coefficient of variation reported by various researchers. The sources of variability in soil properties differ, and accordingly the coefficients of variation differ for different properties.

It can be seen that the variation of C_v for the results of the Standard Penetration Test (N), which is basically a super heavy dynamic probe test, is reported to be between 27 and 85% with a recommended standard of 30%, (Lee *et al.* 1983).

The repeatability of SPT test results could be used as a measure of the repeatability of Mackintosh Probe results by comparing the C_v values of the two methods. In the present research, the values of C_v have been determined for each depth in each series of tests performed at very close proximity. The frequency histogram of the C_v results is shown in Figure 5. The

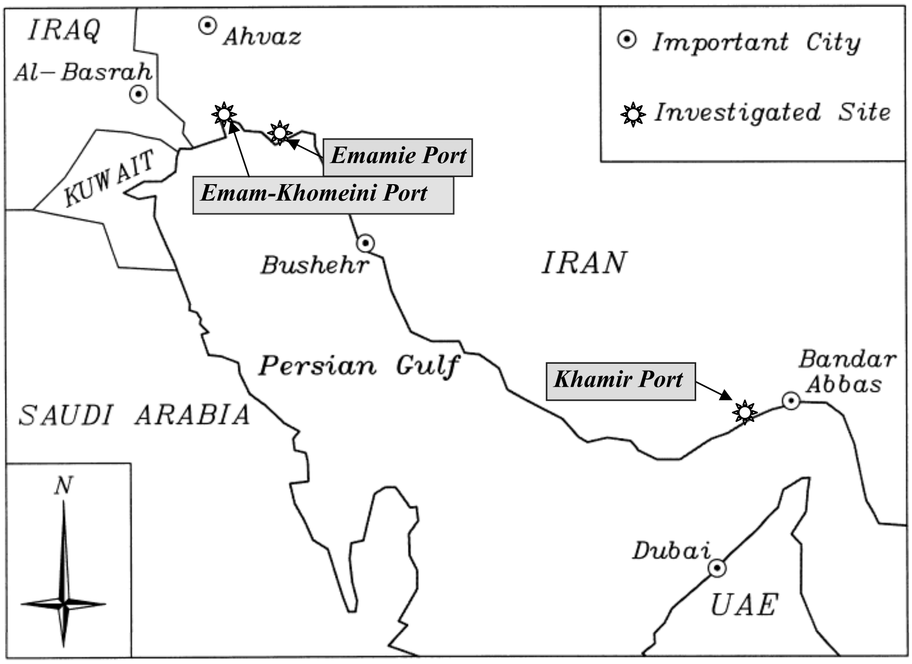

Fig. 2. Site Location.

Pearson-coefficient of variation in Figure 5 represented by r is root of R^2 which is explained later in this paper (Equation 3).

The average value of C_v is about 17%, and its standard deviation is 9.2%. In more than 90% of tests, the value of C_v lies between 2 and 32%. If $(\bar{x})$ and (s) represent the average and standard deviation of C_v respectively, the range of variation can be shown to be:

$$\bar{x} \pm 1.64s$$

In the tests undertaken, the values of C_v vary between 0 and 38% and in most case are less than 30%. Therefore, the results of Mackintosh Probe tests for the three sites can be considered as repeatable results when compared with the values presented in Table 2.

Correlation between *N* and *M*

Chan & Chin (1972) derived an empirical correlation between the results of the Standard Penetration Test (N) and the Mackintosh value (M) for clays as follows:

$$N = 1.8 + .09M \qquad (2)$$

A drawback of Equation 2 is that as M=0, N=1.8, which is not logical. It suggests that Equation 2 should

Table 1. *Soil properties of the investigated sites.*

Site	Depth (m)	Soil Description	Density t/m^3	w %	LL %	PL %	PI %	C_u kPa	Date
Emamie Port	2.5	Soft to very soft brown silty clay	1.88	32	27	20	7	18	2000
	5		1.96	41	25	18	7	23	
	7.5		1.89	37	39	23	16	32	
	10		1.88	36	38	19	19	46	
Khamir Port	2	Lean clay with silt	1.85	31	29	20	9	10	1999
	5		1.91	35	44	22	22	23	
	7		1.95	39	42	25	17	30	
Emam-Khomeini Port	3	Soft to medium clay with silt	1.80	30	45	26	19	48	2000
	5		1.98	28	32	20	12	60	
	8		1.96	31	34	18	16	40	
	12		1.99	29	25	16	9	48	

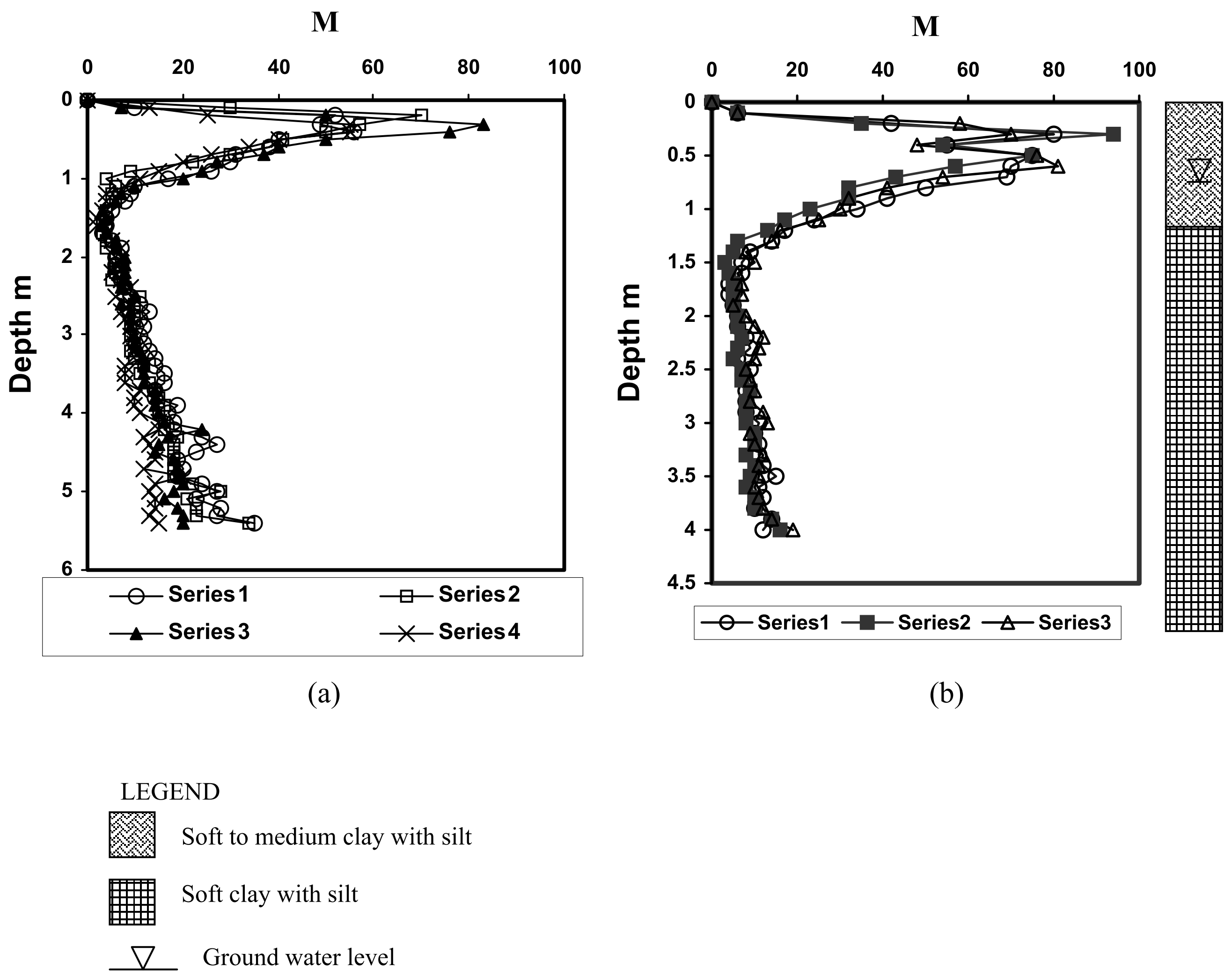

Fig. 3. Examples of the result of tests repeated at close proximity at Emamie Port (a) Four series of tests at point 1; (b) Three series of tests at point 2.

not be used for low values of M. The correlation coefficient (R^2) of Equation 2 is 0.78, which is determined by (Baecher & Christian 2003):

$$R^2 = \left(\frac{\Sigma(x - \bar{x})(y - \bar{y})}{\sqrt{[\Sigma(x - \bar{x})^2 . \Sigma(y - \bar{y})^2]}}\right)^2 \quad (3)$$

Where:

x the value of N obtained from Equation 2
y the value of measured N

The data presented by Chan & Chin (1972) as mentioned by Sabtan & Shehata (1994) suggests a log-normal distribution. Accordingly, Sabtan & Shehata (1994) proposed a relationship between log$M$ and log$N$ using the results of tests in Saudi Arabia and also the data presented by Chan & Chin (1972) for Malaysian clays identified:

$$\log N = 0.91 \log M - 0.79 \quad (4)$$

Equation 4 can be rewritten as:

$$N = 0.16 M^{0.91} \quad (5)$$

The correlation coefficient (R^2) of Equation 5 is 0.85.

The results presented by Sabtan & Shehata (1994) have been combined with the authors' data from the sites Khamir, Emamie and Emam-Khomeini Port. These data also show that a correlation exists between log$M$ and log$N$ rather than M and N. Using the data obtained in the current research and the data presented by Sabtan & Shehata (1994), a new relationship can be determined as shown in Figure 6:

$$\log N = 0.96 \log M - 0.81 \quad (6)$$

Equation 6 can be rewritten as:

$$N = 0.15 M^{0.96} \quad (7)$$

The correlation coefficient (R^2) of Equation 6 (with more data relative to Equation 4) is 0.93.

Equations 4 and 6 suggest that good correlations exist between the results of Mackintosh Probing and SPT in two distinct geographical regions. The authors' data

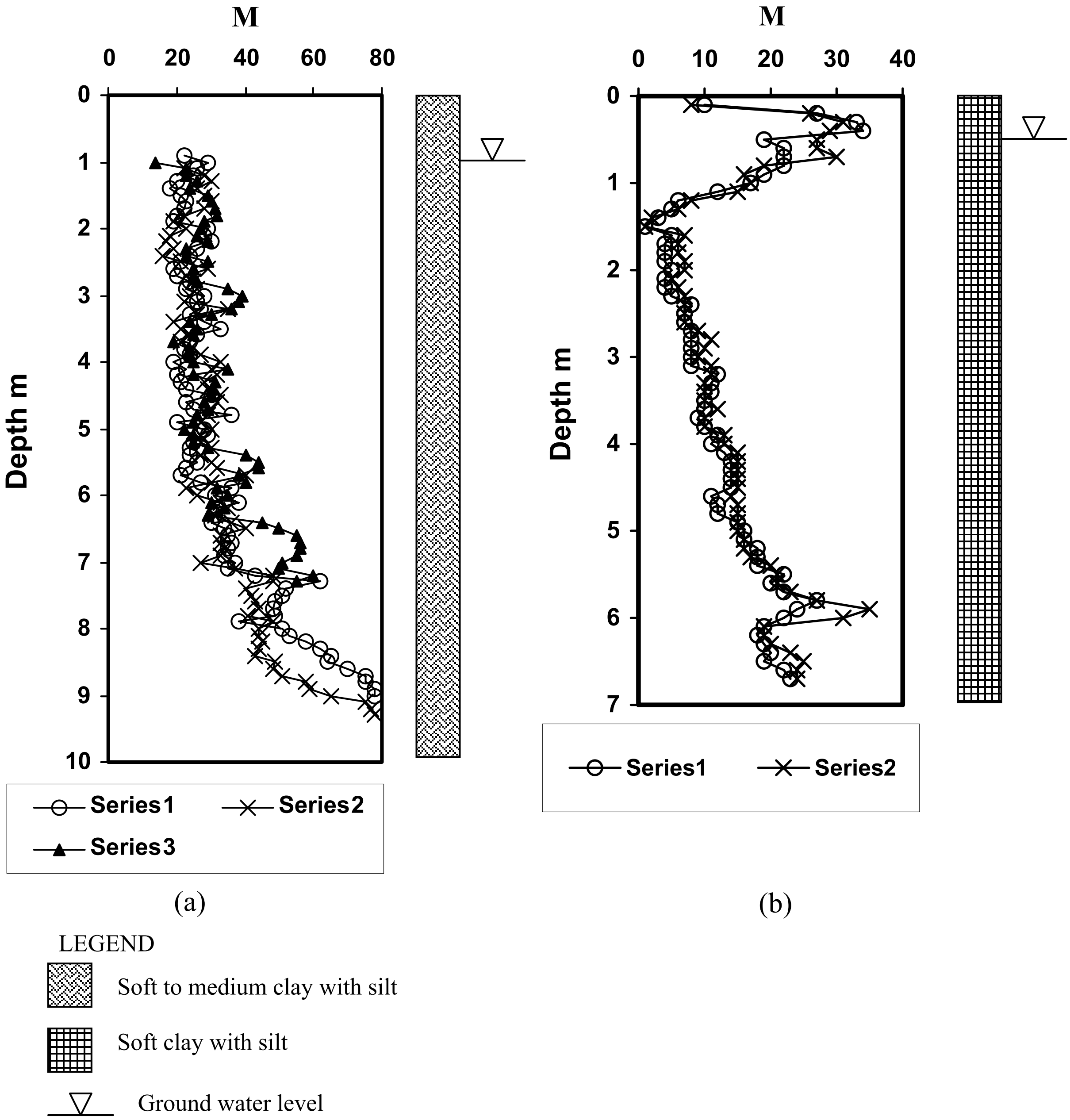

Fig. 4. Examples of the result of tests repeated at close proximity (a) At Emam-Khomeini Port (b) At Khamir Port.

present a similar trend to data from Malaysian clays, which are presented by Sabtan & Shehata (1994).

The results of the Standard Penetration Test are not corrected because it is not usual to correct results for overburden in cohesive soils (Das 1997; Chen 1999). Correction for ground water is also not used (Bowles 1996). No correction for energy was undertaken because no energy measurement was done.

Table 2. *Coefficient of variation for soil engineering tests (Lee et al. 1983).*

Test	Reported Cv (%)	Recommended Standard
Angle of friction (sands)	5–15	10
CBR	17–58	25
Undrained cohesion (clays)	20–50	30
Standard penetration test (SPT)	27–85	30
Unconfined compressive strength (clays)	6–100	40

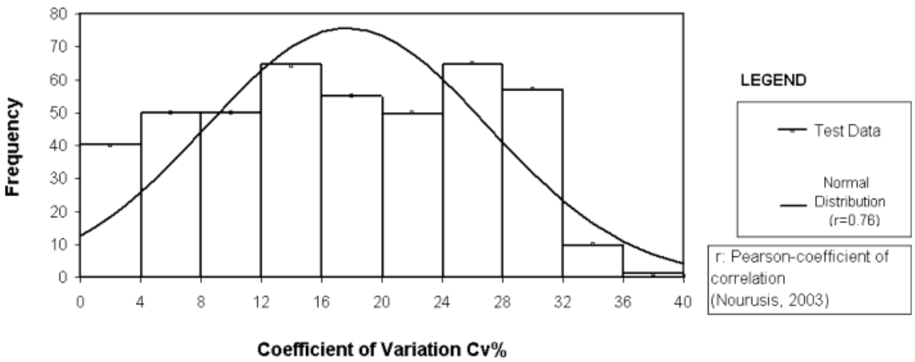

Fig. 5. Normal distribution function for coefficient of variation (C_v).

Relationship between M and c_u

Butcher *et al*. (1995) reported a correlation between the results of all types of dynamic probes and the undrained shear strength (c_u) for soft clays (c_u below 50 kPa) as follows:

$$c_u = (q_d/170)+20 \quad (8)$$

Where q_d is the dynamic point resistance, which is determined using:

$$q_d = \frac{W}{(W+W')} r_d \quad (9)$$

$$r_d = \frac{W.g.h}{A.e} \quad (10)$$

Where:

r_d is the unit point resistance value (Pa)
W is the mass of the hammer (kg)
g is the acceleration due to gravity (m/s^2)
h is the height of fall of the hammer (m)
A is the area at the base of the cone (m^2)
e is the average penetration per blow
W' is the total mass of the extension rods, the anvil and the guiding rods (kg)

Note that the correlation of data for c_u equal to or greater than 50 kPa has not been attempted in the work reported here.

The values of W, h, A and e are equal to 4.5 kg, 0.3m, 6.1×10^{-4} m^2 and $0.1/M$ respectively in case of Mackintosh Probe (g=9.81 m/s$^{2)}$.M represents the number of blows for 100 mm of penetration of Mackintosh Probe.

The undrained shear strength can be determined using Equation 7 assuming that N is related to c_u (kPa) for cohesive soils by (Terzaghi *et al*. 1967):

$$c_u = 6N \quad (11)$$

Substituting the value of N from Equation 7 in Equation 11, the value of the undrained shear strength can be approximated:

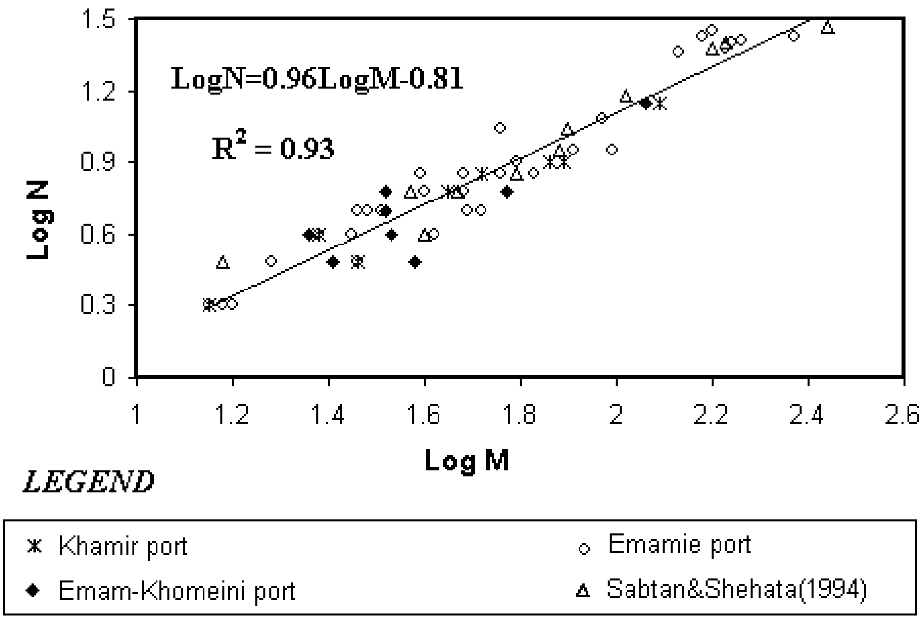

Fig. 6. Log M versus Log N.

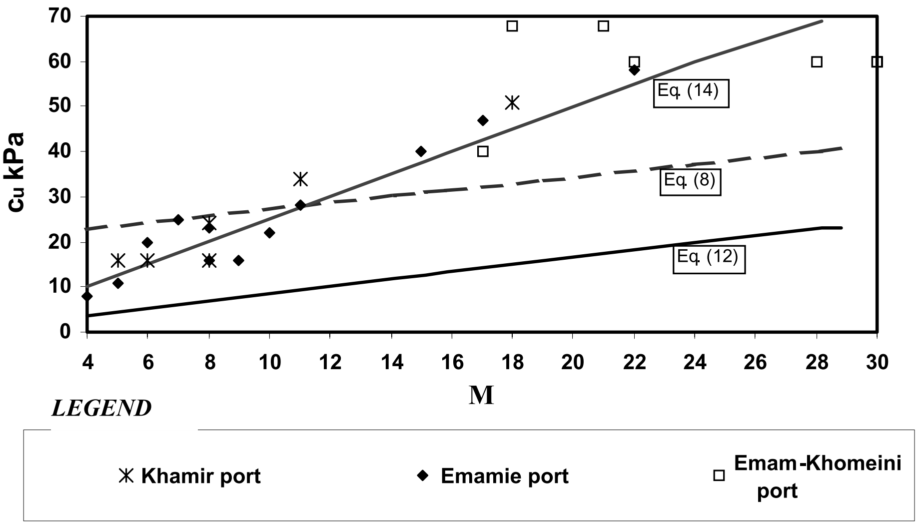

Fig. 7. $M - c_u$ relationship.

$$c_u = 0.90M^{0.96} \quad (12)$$

Hossain & Ali (1988), suggested a relationship between M and undrained shear strength, obtained by a field vane in the form:

$$c_u = K.M \quad (13)$$

Where K is a constant and c_u is measured in kPa.

The authors used the results of other tests including the vane shear test, UU triaxial test and the unconfined compression test with the Mackintosh Probe for comparison leading to the following correlation:

$$c_u = 2.5M \quad (14)$$

Equations 8, 12 and 14 are plotted in Figure 7. The coefficient appearing in Equation 13 varies between 1.8 and 3.5 for the data presented in Figure 7. However, a value of 2.5 is proposed in Equation 14. As shown in Figure 7, Equation 14 is derived for values of M between 4 and 30 and can be shown to be valid only when M value lies between 4 and 30.

It can be seen in Figure. 7 that Equation 14 better represents the data obtained by the authors for the Emamie, Khamir and Emam-Khomeini sites. However, there is not much difference between Equations 8 and 14 when c_u is smaller than 50 kPa and it could be concluded an estimation of the undrained shear strength (c_u) can be made using the results of the Mackintosh Probe in soft soils ($c_u \leq 50$ kPa).

Discussion

The use of dynamic probing in conjunction with trial pits and boreholes can produce information at a low cost. The Mackintosh Probe has a role in site investigations in soft ground due to the low cost and reasonably repeatable results. Mackintosh Probe testing in soft soil has been reported for depths of 0 to 10 m (Kong 1983; Fakher *et al.* 2001).

In addition, M gives an indication of soil parameters. Equations 5 and 7 confirm the existence of correlations between M and N and which Equations 12 and 14 confirm the relationships between M and c_u. The Mackintosh Probe may be successfully used for soft clays with undrained shear strength (c_u) less than 50 kPa. When the Mackintosh Probe is used, it is possible that a value of M greater than 50 can be measured. However, the correlation between c_u and M when $c_u \geq 50$ kPa and $M > 30$ is not discussed in the paper and requires further research.

The value of M for soft clays is higher than the values obtained for N suggesting the M value is more sensitive than N to variations in soil properties. This suggests that Mackintosh Probe testing could be a more appropriate approach than SPT in very soft soils.

If good correlations between soil properties have been established in an area, Mackintosh testing could be used for additional ground investigations. It can also be used for the interpolation of soil properties between boreholes to reduce the cost of investigations by reducing the number of boreholes.

Conclusions

The Mackintosh Probe is a lightweight device, which can be conveniently used for the investigation of soft soil up to depth of 10 m. It can be carried and used in difficult terrain with poor access such as swampy ground, as was the case in this research. The results of Mackintosh Probing can be shown to be both repeatable and indicative of soil strength.

Correlations can be established between M and N and also c_u for soft clays and the Mackintosh Probe can be used rapidly to assess the variability of soil conditions, allowing different conditions to be identified. This allows effective targeting of any subsequent boreholes or tests that may be required and also the interpolation of soil properties between boreholes. Due to the relatively low energy hammer used to drive the probe into the ground the Mackintosh Probe is not a suitable tool for use in hard clay or soils containing gravel or cobbles.

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