MACKINTOSH PROBE AS AN EXPLORATION TOOL

LE PÉNÉTROMÈTRE MACKINTOSH UTILISÉ COMME OUTIL DE RECONNAISSANCE

A.A. SABTAN*, W.M. SHEHATA*

Abstract
A large number of probes, including dynamic penetrometers, are known for exploration and site investigation purposes. The Mackintosh probe is one of the most widespread penetrometers in use in Saudi Arabia. It is light, portable and handy. The purpose of this paper is to present the capability and limitations of this probe. An equation has been derived to relate the Mackintosh M-value with the SPT N-value for cohesive soil. The values of the soil unconfined compressive strength and undrained shear strength can then be deduced with the knowledge of the M-value. For cohesionless soil, correlations were made to determine the relative density, friction angle and unit weight. However, due to the relatively low energy hammer, the Mackintosh probe is not a feasible method of exploring very dense cohesionless material.

Résumé
Un grand nombre de sondes, dont les pénétromètres dynamiques, sont couramment utilisées pour la reconnaissance des sites. Le pénétromètre Mackintosh est l’un des plus utilisés en Arabie Saoudite. Il est léger, portable et facile d’utilisation. L’article présente les possibilités et les limites de ce matériel. Une équation a été élaborée pour corrélérer les valeurs obtenues au Mackintosh (M) à celles obtenues au SPT (N) pour un sol cohérent. Les valeurs de la résistance à la compression simple et de la résistance au cisaillement non drainée peuvent alors être déduites, connaissant les valeurs de (M). Pour les sols sans cohérence, des corrélations ont été faites pour déterminer la densité relative, l’angle de frottement et la masse spécifique. Cependant, en raison de la puissance relativement faible du marteau, le pénétromètre Mackintosh ne s’est pas avéré satisfaisant pour l’étude des matériaux sans cohérence mais très denses.

1. Introduction

Probing or sounding by penetrometers in conjunction with boring, sampling and laboratory testing has been recognized as a valuable technique in soil investigation (Hvorslev, 1949). The continuous sounding profiles may enable easy recognition of dissimilar layers and even thin strata by the observed variation in the penetration resistance in stone or boulder free soils. Further, sounding is generally a considerably faster and cheaper tool than boring specially when the depth of exploration is moderate and the soils penetrated are soft or loose.

Sanglerat (1972) listed a large number of the then available penetrometers and this has greatly increased in recent years. These are either static, or dynamic or both; light weight or heavy weight. These include static ones with either cone alone, cone with friction jacket, or cone with jacket as well as piezometer tips (i.e, piezometer cone).

The standard penetration test (SPT) equipment, with its 2 in (50.8 mm) diameter open ended split spoon, 140 lbs (63.5 kg) hammer and 30 in (0.75 m) drop height (Fletcher, 1965) is one of the earliest and widely used weight dynamic penetrometers. The SPT penetration resistance (i.e. number of blows/0.3 m penetration) designated as the N-value has been correlated, by many authors, with the relative density, and hence other related properties of cohesionless soil and the unconfined compressive strength, qu, of cohesive soils (Terzaghi and Peck, 1967). The quasi-static cone penetrometer developed in Holland and commercially known as the Dutch Cone has undergone significant development in recent years leading to the latest version, the piezocone and it is being used more and more around the world. However, it involves quite large capital investment. The Mackintosh probe (Chan and Chin, 1972) with its 30° apex angle, 1.1 in diameter cone, 4.5 kg hammer and 30 cm drop height (Fig. 1) is a light dynamic cone penetrometer that can be operated manually. Its main

* King Abdulaziz University, Faculty of Earth Sciences, P.O. Box 1744, Jeddah, Saudi Arabia 21441.
advantages are speed of operation and because of its light weight it can be carried and used in difficult terrain with poor access. BSI (1981) recognizes the Mackintosh probe but notes the absence of its standardization or volume of experience in its use. However, Chan and Chin (1972) reported its use, in conjunction with in situ tests, in residual soils of Malaysia. Hossain and Ali (1988 and 1990) used it in a sensitive clay of Obhur Sabkha of Saudi Arabia. Both groups of researchers show how the bottom of a relatively weaker layer of soil could be outlined by the changes in the penetration resistance recorded as M-value. Chan and Chin (1972) derived an empirical correlation between \( N_c \) and \( M_c \) in the form:

\[
N_c = 1.8 + 0.091 M_c \tag{1}
\]

A significant drawback in this equation is that as \( M_c = 0, N_c = 1.8 \), which is not logical. Moreover, equation (1) is valid only if \( N_c \) and \( M_c \) are normally distributed. The fact that equation (1) has a value for \( N_c \) as \( M_c \) equals zero suggests the non-normality of the data.

Hossain and Ali (1988), on the other hand suggested a relationship between \( M_c \)-value and the undrained shear strength, \( S_{uv} \) measured by a field vane in the form:

\[
S_{uv} = K M_c \tag{2}
\]

where \( K \) is a constant having a value ranging between 1.59 and 2.04 with \( S_{uv} \) obtained in kPa.

Equation (2) has a large scatter and the compared values of \( M_c \) are in the range of 2 to 50 whereas the \( M_c \)-values of Chan and Chin (1972) are in the range of 15 to 286 and the number of data pairs is 43 only.

The objective of this work is to examine statistically the data of the above studies in order to avoid the drawbacks of the above relationships for cohesive soils. Another objective is to examine the possibility of some relationships for cohesionless soils. These correlations will allow the conversion of the existing \( N_c \)-value soil property relationships to \( M_c \)-values soil property relationships. The purpose of this last step is to extend some useful charts to include the \( M_c \)-values in order to present rational estimates of soil properties to Mackintosh probe users.

2. Cohesive soil

2.1. Correlation between \( N_c \) and \( M_c \)

The data presented by Chan and Chin (1972) as drawn in Figures 2 and 3 suggests a log-normal distribution of the data. Logarithmic transformations, drawn for both \( N_c \) and \( M_c \) (Fig. 4 and 5 respectively), show that the frequency histograms are symmetrical within the sampling error limits and the fitted curves are normally distributed. The fitted curves show log-normal distributions of both \( N_c \) and \( M_c \) values and suggest that any relationship between \( N_c \) and \( M_c \) should be based on a log \( N_c \)-log \( M_c \) plot (equation 3). This plot is shown in Figure 6.
Equation (4) is graphically shown in Figure 7 to easily deduce the Nc-values from the Mc-values for cohesive soil. The Nc-value calculated by equation (4) and designated as Nc-4 was compared with that obtained from equation (1) of Chan and Chin (1972) and designated as Nc-1. The relative error RE defined by equation (5)
was used as a measure of the difference between the equations (1) and (4).

\[ RE = \frac{(Nc-1) - (Nc-4)}{(Nc-1)} \times 100 \] (5)

The obtained values of \( RE \) as shown in Figure 7 are found to be inversely related to the \( M_c \) values and they are less than 5% when \( M_c \geq 70 \) (or \( N_c \geq 8 \)) which is considered tolerable. A high error of 50% is obtained for \( M_c = 10 \) (or \( N_c = 2 \)). Thus, the \( N_c \)-value calculated by equation (1) will be in serious error for clays of soft to very soft consistencies which corresponds to \( N_c \)-values < 4 according to Terzaghi and Peck (1967).

It may be pointed out that the correlation coefficient is 0.85 for equation 4 compared to 0.78 for equation 1, which proves its superiority.

### 2.2. Useful Relationships

Equation 4 better represents the relationship between \( N_c \) and \( M_c \) for cohesive soil and is used to convert some important relationships or charts that correlate the soil properties with the \( N_c \)-value. The \( N_c \)-values soil consistency relationship presented by Bowles (1982) can then be rewritten for the \( M_c \)-values (Table 1).

Muromachi and Kobayashi (1982) established a relationship between the SPT \( N_c \)-values and the Dutch cone \( q_c \) values for cohesive soil. These results were plotted and subjected to nonlinear regression and curve fitting. The Dutch cone \( q_c \) is related to \( N_c \) by the equation:

\[ q_c = 5.2 \ N_c^{0.9} \] (6)

---

Table 1: Consistency of residual cohesive soil on the basis of Mackintosh \( M \)-values and SPT \( N \)-values.

<table>
<thead>
<tr>
<th>Number of Blows/0.3 m of penetration</th>
<th>Consistency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mackintosh ( M )-value</td>
<td>SPT ( N )-value</td>
</tr>
<tr>
<td>Below 15</td>
<td>Below 2</td>
</tr>
<tr>
<td>15-33</td>
<td>2-4</td>
</tr>
<tr>
<td>33-72</td>
<td>4-8</td>
</tr>
<tr>
<td>72-147</td>
<td>8-16</td>
</tr>
<tr>
<td>147-322</td>
<td>16-30</td>
</tr>
<tr>
<td>over 322</td>
<td>over 30</td>
</tr>
</tbody>
</table>

Table 2: Empirical values for \( q_u \) and consistency of residual cohesive soils based on the \( M \)-value.

<table>
<thead>
<tr>
<th>Consistency</th>
<th>Very soft</th>
<th>Soft</th>
<th>Medium</th>
<th>Stiff</th>
<th>Very stiff</th>
<th>Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_u ) (kPa)*</td>
<td>(25)</td>
<td>(50)</td>
<td>(100)</td>
<td>(200)</td>
<td>(400)</td>
<td></td>
</tr>
<tr>
<td>( M )-value</td>
<td>0</td>
<td>15</td>
<td>33</td>
<td>72</td>
<td>147</td>
<td>322</td>
</tr>
<tr>
<td>( \gamma_{sat} ) (kN/m³)**</td>
<td>(16-19)</td>
<td>(17-20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Unconfined compressive strength established as \( q_u = KN \) where \( K = 12.5 \) (Terzaghi and Peck, 1967).

** Undrained shear strength established as \( S_u = 0.5 q_u \) (Terzaghi and Peck, 1967).
The unconfined compressive strength \((q_u)\) for the cohesive soil is related to the Standard Penetration \(N_c\)-value by equation (7) (Terzaghi and Peck, 1967).

\[
S_{uv} = 12 N_c \tag{7}
\]

Table 2 shows the empirical values for \(q_u\) and consistency of cohesive soils based on the \(M_c\)-value.

If the undrained shear strength \((S_{uv})\) is assumed to be half of the unconfined compressive strength (Terzaghi and Peck, 1967), equation (7) becomes:

\[
q_u = 6 N_c \tag{8}
\]

Substituting the value of \(N_c\) from equation (4) in equation (8), the value of the undrained shear strength can be approximated:

\[
S_{uv} = 1.02 M_c^{0.91} \tag{9}
\]

3. Cohesionless soil

3.1. Correlation between \(N_n\) and \(M\)

The Mackintosh probe has been calibrated for cohesionless soil based on the results given by Geol (1982). The following equation describe the curves for the cohesionless soil:

\[
q_c = 3.2 N_n^{1.2} \tag{10}
\]

The inter-relationship between the \(N_c\) for clay and \(N_n\) for sand values should be the same for the same probe. In other words, the ratio \(N_c/N_n\) for the SPT should be equal to that for \(q_c\) and also for Mackintosh. Therefore, by equating 6 and 10, for the same value of \(q_c\), the \(N_n\) value for cohesionless soil can be related to that of cohesive soil (\(N_c\)):

\[
5.2 N_c^{0.9} = 3.2 N_n^{1.2} \tag{11}
\]

or

\[
N_c^{0.9} = 0.62 N_n^{1.2} \tag{12}
\]

Substituting for the value of \(N_c\) from equation 4, the following equation can be obtained for cohesionless soil:

\[
N_n = 0.39 M^{0.73} \tag{13}
\]

3.2. Useful Relationships

Equation 13 is used to correlate some of the mechanical properties of cohesionless soil and to convert some important parameters of charts that correlate the soil properties with the \(N\)-value. The relationship between relative density and \(N\)-values given by Bowles (1982) has been converted to \(M\)-values (Table 3). Table 4 demonstrates the empirical values for \(\varphi\), \(D_r\), and unit weight of cohesionless soils based on the \(M\)-value.

4. Conclusions

The Mackintosh Probe is a light penetrometer that is fast and tolerably reliable for exploration of most soil types. Better correlations were obtained between the SPT \(N\)-value and the Mackintosh \(M\)-value for clays after logarithmic transformation was used. A relatively reliable equation was also developed for cohesionless soil. However, due to the relatively low energy of the hammer, it was not feasible to explore very dense sand or hard clay.

5. References


Table 3: Relative density of cohesionless soil on the basis of Mackintosh \(M\)-values and \(N\)-values.

<table>
<thead>
<tr>
<th>Number of blows/0.3 m</th>
<th>Relative density</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt;24)</td>
<td>&lt;4</td>
</tr>
<tr>
<td>40-85</td>
<td>4-10</td>
</tr>
<tr>
<td>100-383</td>
<td>10-30</td>
</tr>
<tr>
<td>300-770</td>
<td>30-50</td>
</tr>
<tr>
<td>&gt;770</td>
<td>&gt;50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Very loose</th>
<th>Loose</th>
<th>Medium</th>
<th>Dense</th>
<th>Very dense</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative density ((D_r))</td>
<td>0</td>
<td>0.15</td>
<td>0.35</td>
<td>0.65</td>
<td>0.85</td>
</tr>
<tr>
<td>(M)-value</td>
<td>24</td>
<td>28</td>
<td>45</td>
<td>60</td>
<td>770</td>
</tr>
<tr>
<td>(N)-value</td>
<td>4</td>
<td>10</td>
<td>30</td>
<td>50</td>
<td>770</td>
</tr>
<tr>
<td>Approx. angle of internal friction ((\varphi))</td>
<td>25-30°</td>
<td>27-32°</td>
<td>30-35°</td>
<td>35-40°</td>
<td>38-43°</td>
</tr>
<tr>
<td>Approx. range of moist unit weight ((kN/m^3))</td>
<td>11-16</td>
<td>16-18</td>
<td>17-20</td>
<td>17-22</td>
<td>20-23</td>
</tr>
</tbody>
</table>

Table 4: Empirical values for \(\varphi\), \(D_r\) and unit weight of cohesionless soils based on the \(M\)-value.


