Relationships ($c_u - w$) and ($c_u - \delta$) for remoulded clayey soils at high water content *

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SUMMARY: The note deals with some corollaries of the uniqueness, pointed out by Nagaraj and Jayadeva, of the modified flow lines obtained through normalization of water contents by liquid limit values. The study of many soils of varying plasticity of Southern Italy has confirmed this concept of uniqueness and allowed, besides a new relationship for determining liquid limit using the cone penetrometer method [BS 1377, 1975] by just one penetration, the possibility (i) of determining, in the range of high water contents, the remoulded undrained shear strength as a function of the ratio w/w_L and (ii) of using the cone penetrometer to measure the undrained shear strength.

1. Introduction

As it is known, the number of blows N required to close the groove in the percussion cup liquid limit device or the depth δ in a cone penetration test is a measure of shear strength at different water contents. The water content of saturated clay-water systems is, in turn, a reflection of separation distance d between interacting particles or groups of particles (domains); in this regard, for a texture of uniformly orientated infinite particles or groups of particles the half spacing d can be formally evaluated using the following relationship

$$w = 0.01 \ Sd \qquad (1)$$

where

- w = equilibrium water content (%);
- S = specific surface (m^2/g);
- d = half the separation distance between particles or domains (Å).

The assumption of uniformly orientated infinite units is not met in real cases, except for certain special situation of smectite tactoids, so that the value of d calculated as above does not indicate the true spacing between two units. BAILEY [1965] investigated the effects of finite units (particles) and non parallel orientation. However for real saturated cardhouse or anisotropically textured clay-water systems, d may be considered as a fair indication of the average separation distance. Moreover, general trends in double layer-behaviour are thought to be independent of particle orientation [CHATTOPADHYAY, 1972].

For a soil of surface area S the variation of water content with number of blows or depth of cone penetration can be related to water content at liquid limit such that the effects of surface area are normalized resulting in relationships which are independent of soil type. Such a normalization, in fact, eliminates the effects of surface activity (which are reflected largely by the values of liquid limit w_L) responsible for peculiar and variable responses of various soils at the macro-level. In such a way, and using considerations based on the Gouy-Chapman diffused double layer theory, NAGARAJ and JAYADEVA [1981] showed the uniqueness, irrespective of clay soil type, of the relationship between d/d_L (where d_L is the separation distance at liquid limit) and log N or logδ.

In terms of macroparameters, according to eq. 1, the ratio d/d_L corresponds to w/w_L; this signifies the uniqueness of the normalized flow lines (w/w_L against log N or logδ). Using this rigorous theoretical basis, the Authors suggested the possibility of determining liquid limit, according to the cone penetrometer method [BS 1377, 1975] (Fig. 1), by just one penetration δ, by means of the formula

$$w/w_L = 0.77 \ \log\delta. \qquad (2)$$

2. Re-verification and derivation of further relationships

Figure 2a shows the relationship between water contents (normalized in the described manner) and the corresponding penetrations δ

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of the cone [BS 1377, 1975] for many remoulded soils of Southern Italy covering a wide range of plasticity. The regression equation of the straight line of w/w_L against $\log\delta$ is:

$$w/w_L = 0.102 + 0.688 \log\delta \quad (r^2 = 0.959) \qquad (3)$$

This equation is closely similar to the monomial relationship given by equation (2). This is confirmation of the uniqueness of the modified flow line for all soils. The relationships given by equations (2) and (3) both satisfy the condition $w/w_L = 1$ corresponding to a penetration δ of 20 mm, and both equations allow w_L to be determined from only one penetration with similar negligible inaccuracies relative to the conventional multi-point determination.

For the same soils the remoulded strength c_u has been measured at a range of water contents using a laboratory vane. For soils with liquid limits which vary between 36 and 159%, the measured values of c_{uL} (i.e. c_u at liquid limit water content) fall within the limits of 1.7 to 2.8 kN/m^2, with a concentration of values around 2.28 kN/m^2. These values agree closely with data present in literature, even though different techniques were used [CASAGRANDE, 1958; HAJELA and BHATNAGAR, 1972; NORMAN, 1958; SEED *et al.*, 1964; SKOPEK and TER-STEPANIAN, 1975; YOUSSEF *et al.*, 1965].

In particular, the variation of c_{uL} values with liquid limit practically coincides with the results, obtained through rheological measurements, of HAJELA and BHATNAGAR [1972]. Moreover, the dispersion of c_{uL} values, similarly to the findings of these Authors, is rather large for soils of low plasticity and virtually vanishes when the plasticity increases.

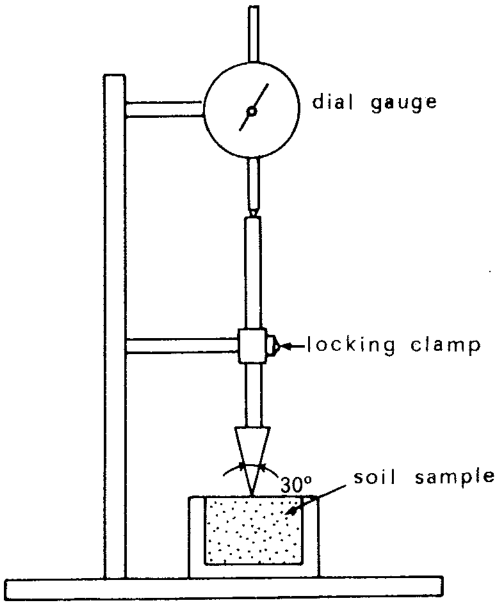

Fig. 1. - BS cone penetrometer.
Fig. 1. - Penetrometro a cono BS.

For any soil, the relationships found between water content w and strength c_u can be expressed as $w = a - b \log c_u$.

When the water contents are normalized by the liquid limit, as indicated in Figure 2b, the following unique relationship is obtained:

$$w/w_L = 1.162 - 0.438 \log c_u \quad (r^2 = 0.971) \qquad (4)$$

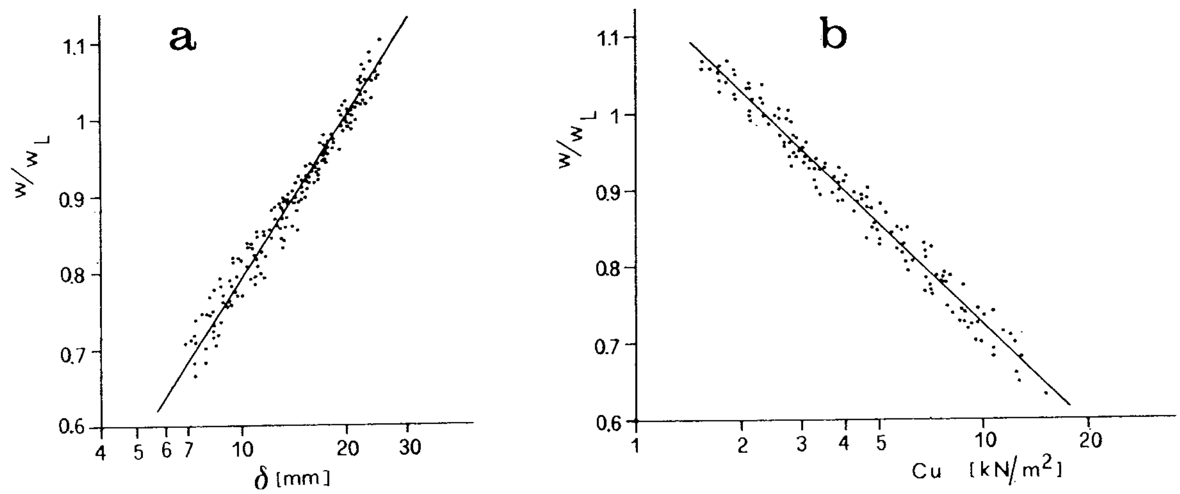

Fig. 2. - Relationships $w/w_L - \log\delta$ (a) and $w/w_L - \log c_u$ (b) for soils of Southern Italy representative of a wide range of plasticity.
Fig. 2. - Relazioni $w/w_L - \log\delta$ (a) e $w/w_L - \log c_u$ (b) per terreni dell'Italia Meridionale rappresentativi di un vasto campo di plasticità.

This relationship can also be represented by the following equation:

$$c_u = \exp 5.25\ (1.162 - w/w_L)\ (kN/m^2) \qquad (5)$$

Relationship (5) is valid for the range of w/w_L values from 0.65 to 1.07.

Furthermore, with δ measured in mm, it follows from equations (3) and (4) that:

$$c_u = 263\ \delta^{-1.57}\ (kN/m^2). \qquad (6)$$

The theoretical equation between c_u and δ, obtained from considerations of the mechanics of penetration [HANSBO, 1957] or from dimensional analysis [WROTH and WOOD, 1978] is

$$c_u = K\,W\,\delta^{-2}$$

where W is the weight of the cone.

In equations (5) and (6) the variations in experimental values are generally within ±10% and reduce considerably where the water content is close to the liquid limit. Finally, from equation (6), the cone penetrometer [BS 1377, 1975] can be used, with close approximation, to measure the undrained strangth. It should be borne in mind, however, that, in this respect, the experimental support is limited to the approximate range of strengths 1.5 to 15 kN/m^2.

3. **Conclusions**

Although limited to the less complex study of the remoulded state, theoretical deductions based on the connection between micromechanicistic parameters and macro-level effects have allowed us to re-verify or derive simple relationships of general validity.

The normalization of water content by means of liquid limit makes the ratio w/w_L useful for first approximate evaluations of remoulded undrained strength, at least in the range of low values of such strengths, irrespective of clay soil type. Moreover the possibility arose of using the simple cone penetrometer [BS 1377, 1975] to measure the strength.

The need for further investigations, as pointed out by FEDERICO [1983], regards mainly the existence of a unique approximate relationship c_u-w/w_L for the whole range of water contents of the saturated clay-water systems.

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SOMMARIO

Relazioni ($c_u - w$) e ($c_u - \delta$) per argille rimaneggiate sature nelle condizioni di elevato contenuto in acqua

Con considerazioni basate sulla teoria del doppio strato diffuso di Gouy-Chapman, NAGARAJ e JAYADEVA [1981] hanno mostrato il carattere unico, qualunque sia il tipo di terreno argilloso, della linea di liquidità modificata ottenuta con normalizzazione per mezzo dei valori del limite liquido. Con tale normalizzazione vengono infatti annullati gli effetti dell'attività di superficie (riflessa in grande misura dal valore del limite liquido) responsabili delle peculiari risposte, al macrolivello, dei vari terreni. Su tale rigorosa base teorica, gli stessi Autori hanno suggerito la possibilità di determinare il limite liquido, secondo la metodologia a cono [BS 1377, 1975] (Fig. 1) attraverso una sola penetrazione δ mediante la formula (2).

La Fig. 2a mostra la relazione tra i contenuti in acqua normalizzati nel modo descritto e le corrispondenti penetrazioni δ del cono [BS 1377, 1975] sul rimaneggiato per un gran numero di terreni dell'Italia Meridionale assai vari per caratteri di plasticità. L'equazione (3) della retta di regressione w/w_L su $\lg\delta$ è sufficientemente prossima alla legge

monomia già citata. Ciò a conferma dell'unicità, per tutti i terreni, della linea di liquidità modificata. Entrambe le leggi soddisfano la condizione di $w/w_L = 1$ in corrispondenza di un affondamento $\delta = 20$ mm ed entrambe si prestano alla determinazione di w_L attraverso una sola penetrazione, praticamente con gli stessi trascurabili scarti rispetto alla determinazione usuale a più punti.

Per gli stessi terreni, ancora allo stato rimaneggiato ed a vari contenuti in acqua, si è fatto luogo a misure di resistenza c_u attraverso il « vane » di laboratorio.

Al limite liquido, e valori dello stesso da 36 a 159%, il campo di variazione di c_u è delimitato da $1.7 \div 2.8$ kN/m², con valori più frequenti attorno a 2.28 kN/m². Tali valori sono in accordo con gli analoghi, ottenuti con tecniche differenti, presenti in letteratura [CASAGRANDE, 1958; HAJELA and BHATNAGAR, 1972; NORMAN, 1958; SEED *et al.*, 1964; SKOPEK and TER-STEPANIAN, 1975; YOUSSEF *et al.*, 1965].

La relazione tra contenuto in acqua e resistenza c_u è, per ogni singolo terreno, esprimibile come $w = a\text{-}b \lg c_u$; normalizzando i contenuti in acqua per mezzo del limite liquido e considerando la totalità dei terreni (Fig. 2b) si ottiene un'unica relazione a validità generale (eq. 4) che può esprimersi come

$$c_u = \exp. 5.25\ (1.162 - w/w_L) \qquad (\text{kN/m}^2) \quad (5)$$

La relazione (5) è valida nel campo dei valori di $w/w_L = 0.65 \div 1.07$.

Ancora, dalle (3) e (4)

$$c_u = 263\ \delta^{-1.57} \qquad (\text{kN/m}^2) \quad (6)$$

con δ misurato in mm.

Gli scarti delle equazioni (5) e (6) sui valori sperimentali sono in generale contenuti nell'ordine ± 10% e diminuiscono sensibilmente per contenuti in acqua prossimi al limite liquido. Da ultimo, mediante la relazione (6), il penetrometro a cono [BS 1377, 1975] può essere usato con buona approssimazione come misuratore delle resistenze non drenate nel campo dei bassi valori delle medesime ($1.5 \div 15$ kN/m²).