A comment on undrained residual strength*

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SUMMARY: The paper presents an observation, deriving from considerations of the diffused double layer theory, which allows the determination of the peak remoulded undrained and residual undrained shear strenghts from a knowledge of the normalized ratio w/w_L alone. The results obtained are based only on literature data regarding London Clays. The subject naturally needs further experimental confirmation on other and different clay materials.

1. Introduction

When most natural soils are subjected to shear deformations, their strength decreases after the peak until, at large strains, an ultimate or residual value is reached, irrespective of whether conditions are drained or undrained (brittle behaviour). However, while the drained residual shear strength has been extensively studied, comparatively little attention has been given to the undrained residual strength.

BISHOP [1972] introduced the term « Brittleness Index » $I_B = [(c_u)_p - (c_u)_r]/(c_u)_p$ for undrained conditions and indicated that this parameter is relevant to the study of progressive failure in rapid loading. In this regard, stress analysis indicates that shear stress along a potential failure surface is non-uniform, whereas τ/σ_n is relatively uniform; thus progressive failure is more critical in undrained than in drained failure [MENZIES, 1982].

Moreover, undrained conditions prevail in many instances where instability occurs on old slip surfaces, and this is clearly important in earthquake loading conditions. In such cases, a total stress stability analysis using $\Phi_r = 0$ and a strength equal to the undrained residual strength c_{ur} can be appropriate and the actual pore pressure values on the slip surface can be ignored.

The residual condition is associated, by definition and by experimental observations, with a reorientation of clay plate units and with the destruction of cementation and/or diagenetic bonds along the surface of shearing.

On the other hand, knowledge of the remoulded peak value of undrained cohesion c_u is of values as a framework against which observed shear strengths (for example from offshores samples) can be judged for their consistency and reliability [WROTH, 1979]. Lastly, because soil placed as a fill undergoes mechanical working, the remoulded undrained shear strength of a soil is considered to be of more relevance to the suitability of soils in embankment than the undisturbed strength [DENNEHY, 1978].

2. The parameters c_u and c_{ur} as a function of the ratio w/w_L

On the basis of diffused double layer theory, NAGARAJ and JAYADEVA [1981] showed, for saturated clay-water systems, the uniqueness of the relationship between w/w_L (where w and w_L are respectively water content and liquid limit) and the logarithm of deviator stress or shear strength. Such relationship must be valid « a fortiori » for the residual condition in which, at least for a band of limited thickness, there is the best orientation of clay particles as assumed by the above-mentioned Authors.

Figure 1 shows the relationship, on a semilogarithmic scale, between water content w and the parameters c_u (peak remoulded) and c_{ur} (residual) taken from BISHOP [1972] for four soils ($w_{L1}=73\%$; $w_{L2}=70\%$; $w_{L3}=79\%$; $w_{L4}=66\%$) from the London Clay formation (*).

If the water contents are normalized with respect to the liquid limit, the points align almost perfectly along two straight lines (Fig. 2) with the following equations:

$$w/w_L = 0.834 - 0.2 \log c_u \quad (r^2 = 0.995) \qquad (1)$$

$$w/w_L = 0.785 - 0.2 \log c_{ur} \quad (r^2 = 0.993) \qquad (2)$$

(*) For the type and method of test, see said Author.

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from which

$$c_u = \exp 11.45\ (0.834 - w/w_L)\ (kN/m^2) \qquad (1')$$

$$c_{u_r} = \exp 11.45\ (0.785 - w/w_L)\ (kN/m^2) \qquad (2')$$

These equations are valid in the range of water contents $w = (0.25 \text{ to } 0.6)w_L$.

In the range of water contents $w = (0.65 \text{ to } 1.07)w_L$, FEDERICO [1983] demonstrated the validity, irrespective of soil type, of the following relationship for the (laboratory vane) remoulded peak undrained strenght:

$$c_u = \exp 5.25\ (1.162 - w/w_L) \qquad (3)$$

Therefore the extrapolation of equation (1′) into the range of w-values mentioned above seems a conservative one.

The existence of two distinct relationships (1′ and 3) for the remoulded strength in the two ranges of water content can be accounted for not only by the different methods by which c_u-values have been measured, but also probably by a different degree of influence of the net interparticle attractive forces in the range of high values of w. However, this aspect needs further study.

3. Concluding remarks

It is of considerable interest to note that the values of undrained peak remoulded and residual strengths presented by Bishop can be very closely determined simply from a knowledge of the normalized ratio w/w_L.

A further aspect from the analysis of Bishop's data is that the influence of microtextural characters on the values of undrained strength is indicated by a constant ratio of the peak and residual strengths related to the same normalized water content; for the London Clay, this ratio of peak remoulded and residual strength is about 1.78.

The theoretical arguments, which have been verified in the range of high values of the ratio w/w_L [FEDERICO, 1983], lead us to believe that equations (1′) and (2′) can be considered as generally valid, eliminating from them the character of statistical relationships valid within the limits of a formation. It is nevertheless necessary to perform further experiments before final comments can be made on this topic.

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SOMMARIO

Una osservazione sulla resistenza al taglio residua non drenata

Per la maggior parte dei terreni naturali ha luogo, dopo un picco, una perdita di resistenza sino ad un valore ultimo o residuo al procedere delle deformazioni di taglio, siano esse in condizioni drenate oppure no. BISHOP [1972] ha introdotto l'« Indice di Fragilità » $I_B = [(c_u)_p - (c_u)_r] / (c_u)_p$ per il taglio non drenato e lo ha indicato parametro rilevante per lo studio della rottura progressiva nel caricamento rapido.

La condizione residua è associata, per definizione e riscontri sperimentali, ad una riorientazione delle particelle d'argilla ed alla distruzione dei legami di cementazione e/o diagenetici lungo la superficie di scorrimento.

NAGARAJ e JAYADEVA [1981] hanno mostrato, sulla base della teoria del doppio strato diffuso, l'unicità, per i sistemi argilla-acqua saturi, della relazione tra w/w_L ed il logaritmo dello sforzo deviatorico o della resistenza al taglio. Tale relazione deve valere « a fortiori » per la condizione residua nella quale, almeno per una banda di limitato spessore, si realizza la migliore isorientazione particellare posta a premessa dai predetti Autori.

La Fig. 1 mostra la relazione, in un piano semilogaritmi-

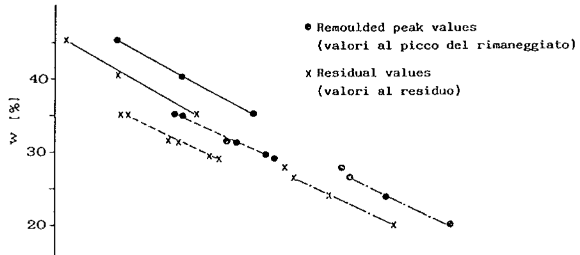

Fig. 1. - Diagram of the relation, based on the BISHOP [1972] data for different samples of London Clays, between water content w and remoulded peak strength c_u or residual c_{u_r}.

Fig. 1. - Diagramma della relazione, basata sui dati ottenuti da BISHOP *[1972] per differenti campioni di London Clays, tra contenuto in acqua w e resistenza di picco rimaneggiata c_u ovvero residua c_{u_r}.*

co, tra i contenuti in acqua w ed i parametri c_u (picco del rimaneggiato) e c_{u_r} (residuo), tratti da Bishop [1972], per 4 terreni ($w_{L1} = 73$; $w_{L2} = 70$; $w_{L3} = 79$; $w_{L4} = 66\%$) appartenenti alla formazione delle « London Clays ».

Se i contenuti in acqua w vengono normalizzati per mezzo del limite liquido, ne risulta l'allineamento pressoché completo dei punti rappresentativi lungo due rette distinte (Fig. 2) di equazione, rispettivamente, (1) e (2). Da esse,

$$c_u = \exp 11.45\ (0.834 - w/w_L) \quad (kN/m^2) \quad (1')$$

$$c_{u_r} = \exp 11.45\ (0.785 - w/w_L) \quad (kN/m^2) \quad (2')$$

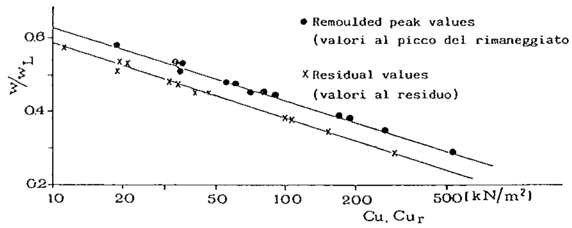

Fig. 2. - Same as fig. 1 after normalization of water content by means of liquid limit.

Fig. 2. - Idem di fig. 1 dopo normalizzazione del contenuto in acqua mediante il limite liquido.

valide nel campo di contenuti in acqua $w = (0.25 \div 0.6)\ w_L$.

Nel campo dei valori di contenuto in acqua $w = (0.65 \div 1.07)\ w_L$ è stato già mostrato [Federico, 1983] il carattere di validità, indipendentemente dal tipo di terreno, della relazione

$$c_u = \exp 5.25\ (1.162 - w/w_L) \quad (3)$$

relativamente alla resistenza non drenata di picco del rimaneggiato; sicché ha carattere conservativo l'estrapolazione della (1') nel campo dei valori w testè citato.

Altro aspetto che scaturisce dall'analisi dei dati di Bishop è che l'influenza dei caratteri microtessiturali sui valori della resistenza non drenata si manifesta con un valore costante del rapporto delle resistenze connesse ad un medesimo contenuto in acqua normalizzato; per le « Blue London Clays », quando si considerano i valori del picco rimaneggiato e del residuo, tale rapporto è all'incirca 1.78.

Le motivazioni teoriche, che sono state verificate nel campo degli alti valori del rapporto w/w_L [Federico, 1983], inducono a ritenere le relazioni (1') e (2') di validità generale per terreni rimaneggiati, eliminandone il carattere di relazioni statistiche a validità in ambito formazionale. È tuttavia evidente che occorre procedere alla ulteriore sperimentazione su una pluralità di terreni per esprimersi in modo definitivo in proposito.