Evaluation of shear strength of clayey soils by using their liquidity index

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Abstract It is well known that overconsolidated clays have higher shear strength than unconsolidated clays. The liquidity index makes possible an evaluation of the consolidation degree of clays. However, there is no empirical information about this relation. In this study, clayey soil samples have been collected from various locations and tested. The tests include the determination of liquidity index and shear strength. Obtained parameters were correlated and regression equations were established among liquidity index and undrained shear strength, presenting high coefficients of correlation ($R = -0.93$). So, an equation [$c_u = e^{(0.026-1.21\,I_L)}$] that makes possible a rough evaluation of the shear strength of clayey soils by using their liquidity index value is an improvement.

Résumé Il est bien connu que la résistance au cisaillement des argiles sur-consolidées est plus grande que celle des argiles sous-consolidées. L'indice de liquidité rend possible une évaluation du degré de consolidation des argiles. Mais il n'y a aucune donnée au sujet de cette relation. Dans cette étude, des échantillons de sols argileux ont été prélevés en divers endroits et testés. Les tests concernent la détermination de l'indice de liquidité et de la résistance au cisaillement. Les paramètres obtenus ont été corrélés et l'analyse de régression entre l'indice de liquidité et la résistance au cisaillement a donné des coefficients de corrélation élevés ($R = -0{,}93$). Aussi une équation [$Cu = e^{(0.026-1.21\,I_L)}$] a été établie, permettant d'obtenir une estimation grossière de la résistance au cisaillement de sols argileux en utilisant la valeur d'indice de liquidité.

Keywords Liquidity index · Shear strength · Clay

Mots clés Indice de liquidité · Résistance au cisaillement · Argile

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Introduction

This study considers the possibility of expressing the relationship between the undrained shear strength (c_u) and liquidity index (I_L) of clays by an empirical equation, such that it would be possible to estimate the shear strength of a clay by using its liquidity index. It is considered that Atterberg limit tests are not only convenient but may also provide a cheaper method of assessing the quick undrained shear strength of clays.

It is well known that overconsolidated clays have a higher shear strength than unconsolidated deposits and this is also reflected in the liquidity index by the difference in moisture content. To date, the empirical relationship between the shear strength and the liquidity index has not been established.

In this study, block samples of clayey soil were collected from various locations in Turkey and liquidity index (I_L) and shear strength (c_u) by triaxial compression tests determined. The parameters obtained were correlated and regression analysis was performed to express the best fit relationship between the c_u and I_L. It is considered that this work provides a rough indication of the shear strength of clayey soils by using their liquidity index value.

Material and methods

The materials used in this study were mostly fine-grained alluvial soils from various locations in Turkey (e.g. Sivas, Tokat, Bursa, Zonguldak). Block samples of undisturbed soils were collected from depths of 2 to 4 m. Of the 41 samples collected, 30 were chosen to obtain, as far as possible, similar characteristics. On these, undrained shear strength (c_u), natural water content, plastic limit and liquid limit values were determined by laboratory tests.

The relative consistency of a cohesive soil in the natural state can be defined by a ratio (Eq. 1) called the liquidity index (I_L):

$$I_L = (w_n - w_p)/I_p \qquad (1)$$

In this equation, if $I_L = 1.0$, the soil is at its liquid limit; if $I_L = 0$, the soil is at its plastic limit. The liquidity index is believed by many authors to more usefully reflect the properties of plastic soil than the generally used plastic and liquid limits (w_p and w_L). The Atterberg tests are carried out on remoulded soil in the laboratory, but the same soil, in its in-situ state, may exhibit a different consistency at the same moisture content due to sensitivity effects. For this reason, it does not necessarily imply that a soil found to have a liquid limit of 50% will be in liquid state if its in-situ water content is also 50%.

If w_n is greater than the test value of w_L then I_L is >1.0 and it is obvious that if the soil was remoulded it would become a slurry. Such a soil would probably be an unconsolidated sediment with a c_u value in the order of 15–50 kPa. Most cohesive soil deposits have I_L values within the range 1.0–0.0. The lower the value of w_n, the greater the amount of compression that must have taken place and the nearer I_L will be to zero. If w_n is less than the test value of the plastic limit, then $I_L < 0.0$ and the soil cannot be remoulded (as it is outside the plastic range). In this case the soil is most likely to be a compressed sediment. Soil in this state will have a c_u value varying from 50 to 250 kPa (Smith 1990).

Rominger and Rutledge (1952) and Means and Parcher (1963) consider that the liquidity index provides a reliable indication of the degree of consolidation of clayey soils. Means and Parcher (1963) reported that $I_L = 0$ for overconsolidated clays and the value of the liquidity index is negative for highly overconsolidated clays.

The undrained shear strength increases with the effective overburden pressure in normally consolidated clay deposits, and a statistical relationship (Eq. 2) for the undrained shear strength, the effective overburden pressure and the plasticity index of the soils is possible (Skempton 1957). Equation (2) is an extremely useful relationship. If the plasticity index of a normally consolidated clay deposit is known, then the variation of undrained shear strength with depth can be estimated (Das 1994).

$$(c_u/\sigma') = 0.11 + 0.0037\, I_p \qquad (2)$$

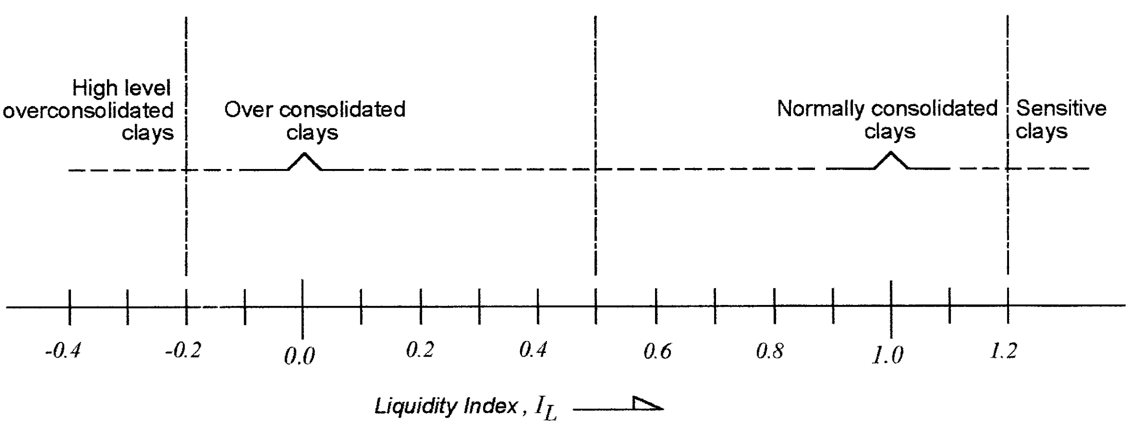
The property that enables a material to remain in equilibrium when its surface is not horizontal is known as its shear strength. Soils in liquid form have virtually no shear strength and even when solid have shear strengths of relatively small magnitudes compared to those exhibited by steel or concrete. Cohesion is a major contributory factor to the shear forces in cohesive soils. The physical state of cohesive soils is expressed by the term consistency; a consistency classification for clays is given in Table 1 (Anon 1979). As shown in Fig. 1 (Means and Parcher 1963), the state of consolidation is indicated by the liquidity index.

In the first stage of the laboratory experiments, grain size distribution, liquid limit, plastic limit and natural water content were determined in accordance with BS 1377 (British Standards Institution 1975). Sieving and hydrometer methods were used to obtain the grain size; the results

Table 1
Consistency of fine-grained soils. (After British Standards Institution 1975)

Approximate undrained shear strength (kPa)	Term
<20	Very soft
20–40	Soft
40–75	Firm
75–150	Stiff
>150	Very stiff or hard

Fig. 1
Relationship between degree of consolidation and liquidity index. (After Means and Parcher 1963)



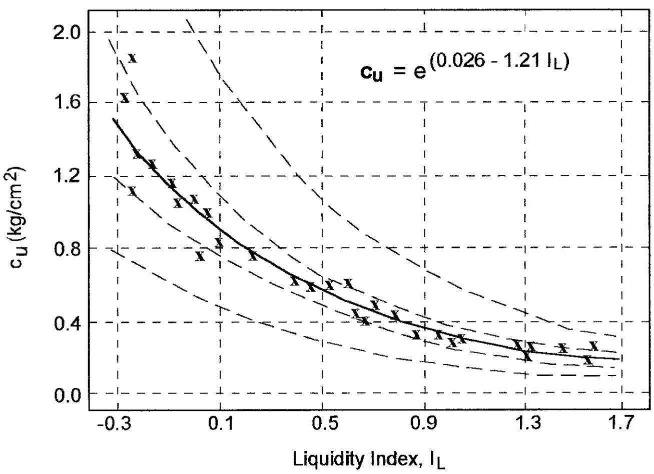


Fig. 2
Relationship between undrained shear strength (c_u) and liquidity index (I_L)

Table 2
Results of regression analyses

Regression analysis-exponential model: Y = exp (a + bX)				
Dependent variable: c_u			**Independent variable: I_L**	
Parameter	**Estimate**	**SE**	**T value**	**Probability level**
Intercept	0.0260579	0.0911338	0.28593	0.77839
Slope	−1.20829	0.109053	−11.0799	0.00000
Correlation coefficient = −0.937212			R^2 = 87.84%	
Standard error of estimate = 0.298599				

indicated the materials to be generally silty clays. In view of its effect on the engineering behaviour of soil, the organic material content was also determined using the Walkey-Black method (Nelson and Sommers 1982). For the fine-grained soils it was found to vary from 0.45 to 0.64%, with an average value of 0.48%. Such a low value would not influence the engineering characteristics of the soils to any significant extent. The plasticity index first increased slightly then decreased with increasing organic content up to 10%.

Results and discussion

Regression analysis of the results comparing the undrained shear strength and liquidity index is shown in Fig. 2. As seen in Table 2, a good correlation is indicated ($R = -0.93$). The relationship between the two parameters is

$$c_u = e^{(0.026 - 1.21\, I_L)} \quad (3)$$

While Fig. 2 indicates a general trend which clearly will be useful for some workers where the Atterberg limits are available, as pointed out by Bell and Culshaw (1998) and Bell and Maud (1995), the liquidity index is a physical property while the shear strength is a mechanical property of the soils and hence empirical methods to obtain the shear strength should always be treated with caution.

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