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A review of factors affecting undrained strength of fine-grained soils at consistency limits

Examen des facteurs qui influent sur la résistance non drainée des sols à grains fins aux limites de consistance.

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ABSTRACT: Estimation of remoulded undrained shear strength of fine-grained soils over a wide range of water content encountered in civil engineering practice is very essential for geotechnical design. Engineers predict the strength through simple index properties, namely consistency limits, rather than using strength evaluated using poor quality soil samples. Though shear strength at two characteristic water contents of practical significance, namely, liquid and plastic limit has found to vary quite significantly, for convenience, strength at these limits has been assumed to be unique. Since, liquid and plastic limit of any soil are nothing but water holding capacity at different states of consistency, undrained strength for different soils having varying liquid limit or plastic limit cannot be expected to have a unique value. In addition to this, recent findings have also brought out the fact that mobilization of strength of soils depends on clay mineralogy and particle gradation. Hence, considering undrained strength of soils to be unique at any consistency limits of soil is not correct. A critical re-examination of factors contributing to the strength and reasons for its non-uniqueness is presented in this paper based on review of data from various well cited articles reported in the literature.

RÉSUMÉ: L'estimation de la résistance au cisaillement non drainée remaniée des sols à grains fins sur un large éventail de teneur en eau rencontrée dans la pratique du génie civil est très essentielle pour la conception géotechnique. Les ingénieurs prédisent la force par des propriétés d'index simples, à savoir des limites de consistance, plutôt que d'utiliser la force évaluée en utilisant des échantillons de sol de mauvaise qualité. Bien que la résistance au cisaillement à deux teneurs en eau caractéristiques d'importance pratique, à savoir, la limite de liquide et de plastique a trouvé pour varier assez sensiblement, pour plus de commodité, la force à ces limites a été supposée être unique. Puisque, la limite liquide et plastique de n'importe quel sol ne sont rien mais la capacité de retenue d'eau à différents États de la consistance, la force non drainée pour différents sols ayant la limite liquide variable ou la limite en plastique ne peut pas être censée avoir une valeur unique. En outre, des découvertes récentes ont également fait ressortir le fait que la mobilisation de la force des sols dépend de la minéralogie de l'argile et de la gradation des particules. Par conséquent, considérant la force des sols pour être unique à n'importe quelle consistance du sol n'est pas correcte. UN réexamen critique des facteurs contribuant à la force et aux raisons de sa non-unicité est présenté dans le présent document, fondé sur l'examen des données provenant de divers articles cités dans la littérature.

Keywords: Clays; consistency limits; fine-grained soils; plasticity; undrained strength.

1 INTRODUCTION

For a proper design and functioning of any civil engineering structure, two geotechnical parameters of concern are: strength and deformation characteristics of the soil; soil, which either is the supporting medium for foundation of the structure, or soil itself is used as an engineering material for the structure. In most of the practical situations, strength controls the deformation behaviour of soils. It is observed that the natural water content of soils is very near to plastic limit water content (Leonards, 1962; Bell, 2002). Even soils used for the construction of earthen embankments can be compacted to achieve maximum dry unit weight at optimum moisture content, which is found to be near to plastic limit of soils (Sridharan and Nagaraj 2005; Nagaraj et al., 2015). Therefore, most of the geotechnical related works with fine-grained natural soils, strength at plastic limit is of concern. On the other hand, there are many practical situations where the evaluation of soil strength at very high-water contents, near to liquid limit is also essential. To cite a few such situations: founding of an offshore structure on soft sediments, handling soft sediments during reclamation of dredged materials (Meriggi et al., 2007). Of late, researchers and engineers have found increased potential in using dredged sediments for various high volume civil engineering applications including: landfill caps and fill, roadway embankments, brownfield caps and fills, and in expanding the port facility(Quiroz et al., 2000; Maher et al., 2013). Such slurry of sediments when deposited by transportation will be having very high-water content, and hence, low strength. As it is impossible to collect undisturbed specimens to directly evaluate their shear strength of such dredged sediment when its consistency is still fluid, this difficulty is overcome by indirectly evaluating undrained shear strength for dredged sediments as a function of their water content by means of relationships with the results of a simple fast laboratory tests, namely vane shear test and the slump test (Meriggi et al., 2007).

Thus, it can be seen that the variation of natural water contents in most of field situations for fine-grained soils falls within the range of liquid limit and plastic limit, popularly known as consistency limits. Therefore, evaluation of shear strength of soils at these limits enables development of strength profile of the soil at various water contents. This paper discusses in detail all the latest reported information from the literature on undrained strength of fine-grained soils to bring clarity about the need to consider all the possible factors influencing the mobilization of undrained strength in fine-grained soils. This would possibly lead to more concerted research for bettering the understanding of the factors influencing undrained strength of soils.

2 VARIATION OF STRENGTH AT CONSISTENCY LIMITS

It can be seen that undrained strength at high water content near to liquid limit has attracted lot of attention to geotechnical engineers for the past eight decades and has led to reporting of the undrained strength at liquid limit through many leading research publications, which are well referred even today. The remoulded undrained strength reported by various researchers is quite varying, for e.g., Skempton and Northey (1952): 0.7 kN/m^2 to 1.75 kN/m^2 for four soils having liquid limit varying between 30 to 97%; Youssef et al. (1965): 1.3 kN/m^2 to 2.75 kN/m^2 for twelve soils having liquid limit varying between 32 to 190%; Wasti and Bezerci (1986): 0.5 kN/m^2 to 5.6 kN/m^2 for 25 soils having liquid limit varying between 27 to 526%. Since the strength at liquid limit is small, it appears averaging out the values is not of big consequence. However, the relative differences in values is quite high, being more than 200 % to 1120%. Even Youssef et al. (1965) have also reportedly stated that: *''although the strength at liquid limit is essentially small, a big relative difference is to be noted''*.

Though, it has been well reported that strength is mainly a function of water content, for convenience a misconception that strength is unique at liquid limit (1.7 kN/m^2) and plastic limit (170 kN/m^2) crept into the geotechnical literature (Skempton and Northey 1952). However, subsequent research works overlooked this mistake, and accepted the concept proposed by Wroth and Wood (1978) of redefining plastic limit in terms of strength as that water content that gives a 100-fold increase in shear strength over that at the liquid limit. This led certain researchers to independently develop instrumented cone penetrometer to determine the plastic limit (Stone et al., 1995; Tefera, 2013). Prakash (2005) brought out the shortcoming of using the arbitrarily fixed strength at liquid and plastic limit to redefine plasticity index instead of rationally determining the plasticity index which represents the real plasticity characteristic. Recently, Nagaraj et al. (2012) tried to re-examine undrained strength at Atterberg limits based on the data available in the literature and brought out the fact that remoulded undrained strength neither at liquid limit nor at plastic limit is unique, nor bear a constant 100-fold increase.

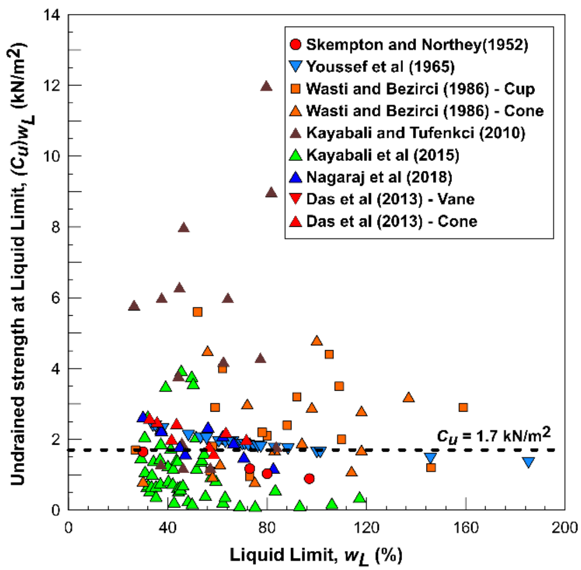

Figure 1. Undrained strength at liquid limit versus liquid limit.

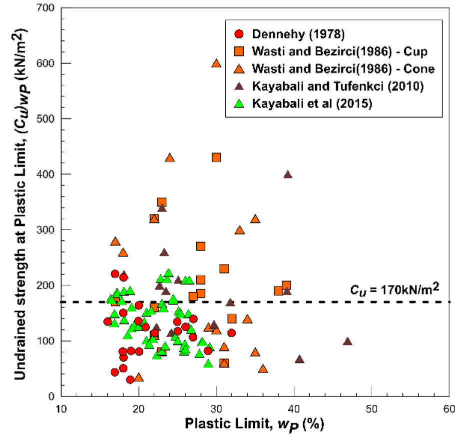

Figure 2. Undrained strength at plastic limit versus plastic limit.

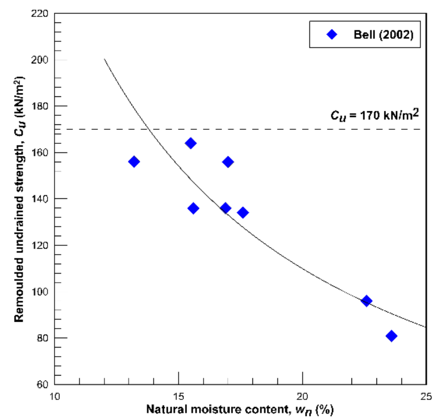

Figure 3. Remoulded undrained strength versus natural water content (Bell 2002).

Fig. 1 and Fig 2 shows the plot of remoulded undrained strength versus liquid limit and plastic limit respectively, based on data taken from well cited publications in the literature. It can be seen that there is a lot of variation in the undrained strength values both at liquid limit and plastic limit from the assumed average values of 1.7 kN/m^2 and 170 kN/m^2 at liquid limit and plastic limit respectively. Fig. 3 is a plot of remoulded undrained strength of natural till deposits at natural water contents, which were very close to their plastic limit (data after Bell 2002). It can be observed from the figure that there is a non-linear decreasing trend of undrained strength with increase in water content of the soil (being very close to their plastic limit) at which the strength is determined, and also the values of strength ranges from 81 to 164 kPa. Fig. 4 is a plot of undrained strength of undisturbed natural clays from Kuttanad area in Kerala state, India (data after Jacob and Hari 2016) versus natural water content, liquid limit and also plastic limit.

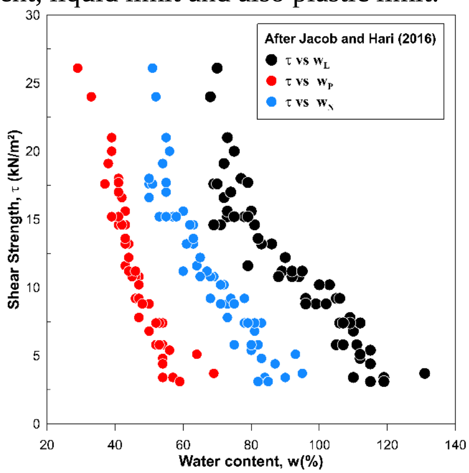

Figure 4. Undrained strength of undisturbed natural clays versus natural water content, liquid limit and plastic limit (Jacob and Hari, 2016).

It can be seen from the figure that: i) the natural water content is in between the liquid limit and plastic limit of soils and ii) the undrained strength has a non-linear decreasing trend with an increase in natural water content/ liquid limit/plastic limit. In case the remoulded undrained strength of those natural clays was determined by remoulding the soils at varying water contents and strength at their respective liquid limit or plastic limit were determined, it would have given similar functional relationship of strength water content, but with a different range of strength as compared to that obtained at natural water content. This clearly brings out the fact that undrained strength of clays, both undisturbed or remoulded cannot be unique as being assumed in the literature and also varies with the liquid limit or plastic limit as they are also water contents at different consistency of soils. Results from Kestler (1982) adds testimony to these observations. Kestler (1982) performed two simple strength tests using pocket penetrometer and hand held torvane on each of the fourteen clay soil samples used in the study to assess the strength at liquid limit obtained by both Casagrande's percussion cup device and cone method. It was observed that there was certainly a decreasing strength at liquid limit with an increase in the liquid limit.

Recently, Haigh et al.(2013) reported that plastic limit does not correspond to a fixed strength and opined that, soil type, especially presence of a significant silt fraction would influence the mechanisms controlling the strength. Though attempts to understand the influence of clay mineralogy on the mechanisms controlling the undrained strength of soils was reported by Sridharan and Prakash (1999), more detailed study to understand the influence of clay mineralogy along with the fabric effect controlled by frictional fractions was recently reported by Nagaraj et al., (2018). Hence, it is imperative that there are various factors that may influence the undrained strength of fine-grained soils at any consistency limits of the soil. Hence, all those factors should be taken into consideration for understanding the large variations in the undrained strengths at the both the extreme limiting water contents of significance to civil engineers. This would enable one to develop a relationship of undrained strength over a wide range of water content.

3 RELATIONSHIP OF STRENGTH WITH LIQUIDITY INDEX

Skempton and Northey (1952) was probably the first to report that remoulded strength of clays principally depends on liquidity index. Later, various researchers reported that strength can be conveniently related with liquidity index of soils (Whyte, 1982; Wood, 1985; Sharma and Bora 2003; Vardanega and Haigh 2014; to name a few). However, a careful scrutiny of the data, which is drawn from various literature sources and used in the paper by Vardanega and Haigh (2014), the following observations can be made:

- Undrained strength of most of the data used for their study, which is drawn from various literature sources do not have directly determined undrained strength at plastic limit. Therefore, the strength at plastic limit has been assumed based on the 100 fold increase in strength at liquid limit suggested by Wroth and Wood (1978).
- Based on these extrapolated strength values, the correlation of undrained strength with liquidity index has been developed.

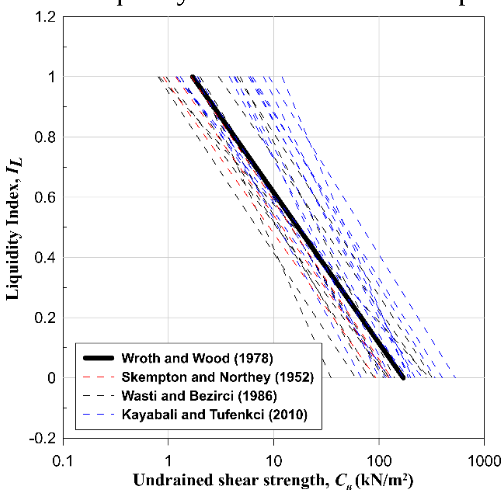

Figure 5. Liquidity index versus undrained strength

Further, to understand the relationship between liquidity index (I_L) and undrained strength (C_U) of all the individual soils using the data from some literature sources (Wasti and Bezerci 1986; Kayabali and Tufenci 2010) were taken and the same plotted as I_L versus C_U on a semi-log plot as shown in Fig. 5. On the same figure, the 100-fold increase in strength between liquid limit and plastic limit as assumed by Wood (1978) has been plotted. It can be seen that, there is a wide variation in strength at $I_L = 1$ (at liquid limit) and $I_L = 0$ (at plastic limit), thereby bringing clarity to the fact that there is no unique strength, either at liquid limit or at plastic limit; nor there is a 100-fold increase in strength between liquid and plastic limits.

4 RELATIONSHIP OF STRENGTH WITH EXTRUSION FORCE

To explore the probable reasons for this deviation of the hitherto assumed 100-fold increase in strength, Kayabali et al., (2015) taking vane shear test as a reference, developed a new mud press machine to evaluate the extrusion force (which they consider akin to undrained strength of soil obtained by vane shear test) required to extrude the saturated soil with varying water content (from liquid limit to plastic limit) from the mud press. From the water content versus extrusion force, the force required at liquid and plastic limits were obtained. For the 60 soils used in their study, they found similarity between the undrained strength versus water content obtained by vane shear and the extrusion force versus water content obtained by mud press.

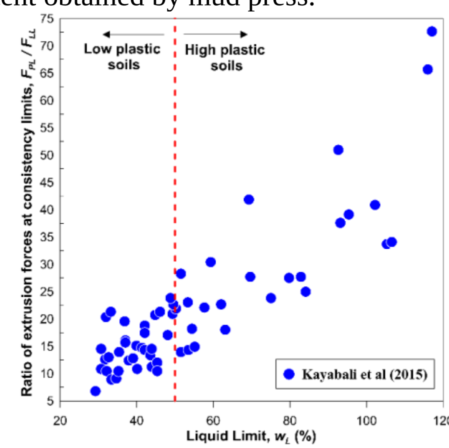

Figure 6. Ratio of extrusion forces at consistency limits versus liquid limit

They observed that there a good non-linear decreasing relationship between extrusion force at the respective consistency limits versus the consistency limit water contents. The authors of the study attribute this behaviour to the plasticity of the soils. Further, the study also reveals that the ratio of the extrusion force at plastic limit and liquid limit bears a good increasing relation with increasing plasticity of the soils, indicated by liquid limit of soils as shown in Fig. 6. They also observed that the ratio is as low as 5 for low plastic soils to as high as 75 for high-plastic soils. Based on the above discussion with the available information in the literature, it becomes evident that there are various factors that influence the mobilization of undrained strength, and they need to be taken into account before developing meaning correlation for prediction of the same.

5 FACTORS INFLUENCING UNDRAINED STRENGTH OF SOIL

From the elaborate information and discussion presented in the previous sections, it is imperative that it is a fallacy to assume that the remoulded undrained strength of fine-grained soils at two important consistency limits, namely liquid limit and plastic limit as unique at 1.7 kN/m^2 and 170 kN/m^2 respectively, irrespective of their values; and that there are various factors that may influence the strength of soils.

Reported findings by Sridharan and Prakash (1999) that there are different mechanisms controlling the strength of the soils based on their clay mineralogy, brought out a new direction in understanding the factors controlling their undrained strength. Recent observations from Nagaraj et al. (2012) based on the re-examination of undrained at both the consistency limits indicated their strength at any of the consistency limits is not unique and there is a need to understand the various factors that may influence undrained strength. New research findings from Kayabali et al. (2015) brought out that plasticity of soils has a significant influence on undrained strength of soils. In this context, it is very interesting to note that, Wood (1985) reportedly states that: *"The more plastic a soil, the greater the change in water content that is required to produce a certain change in strength"*. This clearly indicates that strength of a soil depends on its plasticity, which in turn may depend on the clay mineralogy; as it is well understood that montmorillonitic soils have more plasticity that illitic or kaolinitic soils.

Furthering this understanding Nagaraj et al. (2018) brought out the fact that there are various factors that may influence the undrained strength of soils, including the fabric and the plasticity of the soil. They also observed that the undrained strength is not only having a relationship with liquid limit of soils, but also the functional relationship is different based on the dominant clay minerals present in the soil (Fig 7). This was explained based on how the strength is mobilised: contribution of strength coming from either the mobilisation of net attractive force between the kaolinite clay particles, and frictional resistance offered by coarse particles (as in case of kaolinitic type of soils); or combined contribution coming from the viscous shear resistance as contributed by the diffuse double layer, and the frictional resistance at the particle level (as in the case of montmorillonitic soils). Thus, there is a critical state between frictional particles (like fine sand and silt size fractions) and both the clay mineral type and its proportion in mobilising the strength.

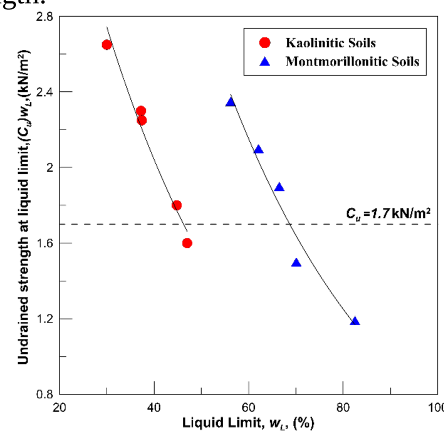

Figure 7. Undrained strength at liquid limit versus liquid limit (Nagaraj et al., 2018)

Very recently, Nagaraj and Suresh (2018) reported the mineralogical influence on the relationship between both California Bearing Ratio (CBR) and Unconfined compressive (UCC) strength with the index properties, namely liquid limit and plastic limit. They have reported that different relationships exist between both CBR/UCC and plasticity properties based on the dominant clay mineral present in the soils. One such relationship is shown in Fig. 8, which is a plot of UCC versus plastic limit of soils. Since CBR and UCC strength are both measure of strength of soils, the mineralogical influence on both CBR and UCC in relation with the consistency limits bears additional testimony to the influence of plasticity on undrained strength.

Thus, the detailed information drawn from the past publications in literature, based on which observations and discussion are presented here evidently reveal that there are various factors that influence the undrained strength of fine-grained soils including*: fabric of the soil as influenced by particle size and gradation; plasticity of the soil as influenced by the clay mineralogy, which in turn dictate the water holding capacity of soil as indicated by the consistency limits*. This needs further detailed studies world over to bring out concurrence to the reported findings.

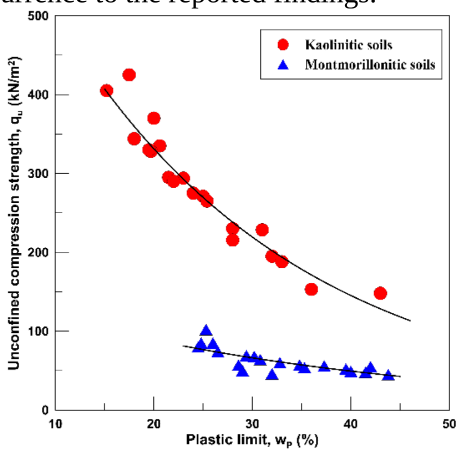

Figure 8. Unconfined compressive strength versus liquid limit (Nagaraj and Suresh, 2018)

6 CONCLUSIONS

The need to know the remoulded undrained strength of fine-grained soils in connection with the development of devices for determining liquid limit attracted lot of research publications to understand the strength of soils at high water content, namely liquid limit. The 100-fold increase in strength at plastic limit as compared to that at liquid limit in spite of the variation in liquid limit was a misconception in geotechnical literature. Based on the detailed discussions presented in this paper using the data available in the published literature, not only brings out this fallacy of uniqueness of strength, but also brings out that there are various factors that may influence the strength of the soil. This encourages more comprehensive studies to be taken up for understanding the various factors contributing to the mobilization of undrained strength. This would help in trying to understand clay–water system in a better way to predict their strength behaviour.

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