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# Discussion of “Re-Examination of Undrained Strength at Atterberg Limits Water Contents” by H.B. Nagaraj, A. Sridharan & H.M.

Mallikarjuna

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Having recently investigated soil strength at the Atterberg limits, the discussers read the paper by Nagaraj et al. (2012) with interest. Whilst some of the conclusions of the paper concur with those of our own work, there are other areas in which we would question the authors' conclusions.

## **STRENGTH AT THREAD-ROLLING PLASTIC LIMIT**

The authors' recognition that soil strength at Atterberg's thread-rolling plastic limit is variable concurs with observations made in Haigh et al. (2013). The stress-state during the Atterberg thread-rolling test is complex, as discussed by Whyte (1982), but the lack of any control on applied stresses during the test implies that it cannot be an assessment of soil strength, merely one of the onset of brittleness. Based on a review of available data for 71 soil samples from published literature, we concluded that the undrained strength at plastic limit could range from 17 kPa to 530 kPa, with an average value of 152 kPa and a standard deviation of 89 kPa, a range even greater than that presented by the authors.

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## STRENGTHS AT FALL-CONE LIMITS

While the thread-rolling test is not a strength measurement, the fall-cone test was shown by Hansbo (1957) to be a measurement of soil strength via the relationship:

$$c_u = \frac{kW}{d^2} \quad [1]$$

where  $c_u$  is the undrained shear strength of the soil,  $d$  is the penetration of a cone of weight  $W$  and  $k$  is a constant. Houlsby (1982) carried out a plasticity analysis of the penetrating cone and confirmed this relationship, also investigating the effect of parameters such as cone angle and bluntness on the results. The definition of liquid limit as corresponding to a particular cone penetration thus implies a particular strength.

Assessment of this strength by other means, such as using a vane-shear apparatus, may show some scatter in the data owing to strain-rate effects and experimental errors, but, provided suitable care is taken, it would be expected that only very small variation would be seen in the strengths measured at the liquid limit. It is thus strange that the authors claim a range of 0.2 kPa to 4.8 kPa for undrained strength at the fall-cone liquid limit.

The extreme low values of this measurement are quoted as being due to Locat & Demers (1988). Inspection of this paper, however, reveals that the strength values quoted are strengths at the natural water content of various samples, not at their liquid limits. Whilst strengths at liquid limit are not explicitly quoted in the paper, all viscometer tests being carried out at water contents greater than liquid limit, the data plotted converges to a remoulded shear strength of around 2 kPa at the liquid limit. The remainder of the experimental data associated with fall-cone plastic limits is that from Wasti & Bezirci (1986), who used a laboratory vane to assess the soil strength at the fall-cone liquid limit. This set of 25 datapoints has a mean value of 2.2 kPa and a standard deviation of 1 kPa. Kravitz (1970) assessed the relative merits of the fall-cone and laboratory vane apparatus in assessing the

strength of very weak cohesive materials, such as those close to their liquid limit. He showed that while the two techniques gave similar mean strengths, the vane shear data showed double the standard deviation of the fall-cone data and thus that the fall-cone was a better tool for assessing the strength of very weak sediments. The data of Wasti & Bezirci (1986) thus calls into question the use of the vane-shear apparatus to assess very low soil strengths at least as much as the theoretically justified assumption of constant strength at liquid limit.

The development of cone penetration tests to assess plastic limit by researchers such as Stone & Phan (1995) also implies the assessment of soil strength. Stone & Phan explicitly recognised that they were measuring a different plastic limit to that described by Atterberg, terming it  $PL_{100}$ , the water content at which the undrained strength is 100 times that at liquid limit. The brittleness of soil at the plastic limit both makes sample preparation difficult and may bring into question the justification, using plasticity theory, that the fall-cone test is a direct measure of strength. Strengths measured using the vane shear apparatus will, however, be similarly affected, so the data of Wasti & Bezirci (1986) may be questionable.

## **STRENGTH AT CASAGRANDE'S LIQUID LIMIT**

While the fall cone test is a measure of the undrained shear strength of soil, the Casagrande cup test for liquid limit is more complex. Haigh (2012) demonstrated from a Newmarkian analysis of the test that the Casagrande liquid limit corresponds to a specific undrained strength (undrained strength divided by density) of around  $1 \text{ m}^2/\text{s}^2$ . As soil density decreases with increasing water content, this implies that soils with a high  $w_L$  should exhibit lower strengths at liquid limit than those with a low  $w_L$ . This tendency is observed to some extent in the data presented in this paper, but to a much greater degree in the dataset of 89 tests from

Norman (1958), Youssef et al. (1965), Sherwood & Ryley (1970), Campbell (1975) and Leroueil & Le Bihan (1996) presented by Haigh (2012).

While Casagrande's liquid limit is thus not associated directly with undrained strength, the value of strength at liquid limit can be estimated if the water content is known.

## VARIATION OF UNDRAINED STRENGTH WITH WATER CONTENT

The presentation of the various equations proposed in the literature for the correlation between undrained strength and water content is welcomed. As the authors note, the variability of undrained strength at the Casagrande plastic limit makes a correlation between Casagrande's liquidity index and strength problematic. The strengths defined at fall-cone liquid and plastic limits, however, may make these correlations worthwhile.

While many of the correlations have wide applicability, several have limitations that were not described in the paper. Specifically, the relationship by Locat & Demers (1988):

$$c_u = \left(\frac{19.8}{I_L}\right)^{2.44} \quad [2]$$

is only valid for liquidity indices  $I_L$  greater than one, and the relationship from Edil & Benson (2009):

$$c_u = 191.4 e^{-(0.03w_L)} \quad [3]$$

is only valid for the soils in this study at their natural water contents, and hence has no wider applicability.

## SUMMARY

In summary, while this paper rightly recognises that Atterberg's thread-rolling plastic limit is not associated with a particular undrained strength, the fall-cone based liquid limit is directly

associated with an undrained strength of around 1.7 kPa. Casagrande's percussion liquid limit occurs at a specific strength of around  $1 \text{ m}^2/\text{s}^2$  and is hence indirectly linked to the undrained strength of the soil.

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