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Discussion of "Reclaimed Lignin-Stabilized Silty Soil: Undrained Shear Strength, Atterberg Limits, and Microstructure Characteristics" by T. Zhang, G. Cai and S. Li

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Introduction

The discussers read with interest the recent paper by Zhang et al. (2018), which reports on the investigation of the effects of 0–12% lignin additive on some index and shear strength properties of a silty soil material. The use of the fall-cone device to study undrained shear strength variation with moisture content is pleasing to see and shows how the approach is useful for this purpose: namely the study of undrained strength variation. We wish to make the following comments regarding some of the underlying assumptions in the paper by way of offering some other explanations and interpretations for the results obtained.

Atterberg Limits

The value of liquid limit (w_L) can be determined using standard percussion cup or fall cone devices and is notionally understood as the moisture content corresponding to the transition from liquid to plastic behavior, though this distinction is arbitrarily defined. The international standard method for the determination of the plastic limit (w_P) value, understood as the moisture content corresponding to the brittle transition point for the soil thread investigated, is the rolling of threads method originally described in Atterberg (1911a, 1911b). These standard tests are performed on the fraction of the *remolded* soil passing the 425 μm sieve (see e.g., BSI, 1990).

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In the authors' investigation for the *7 d cured lignin-stabilized* soil specimens, established strength-based approaches were used to estimate the specimens' moisture content values for two assigned fall-cone penetration depth (*h*) values, with the authors reporting these moisture content values as w_L and w_P. Irrespective of the code of fall-cone practice employed, these values do not correspond to the standard liquid and plastic limit values as described above (O'Kelly et al. 2018), since they do not correspond to the remolded soil state (having been allowed to cure over a 7 day period before being tested undisturbed using the fall cone device) and there are also a number of inconsistencies in the underlying assumptions and methodologies employed by the authors for their determinations, which are discussed in the following paragraphs.

Cone Factor and Fall-Cone Undrained Shear Strength

In their experimental investigation, the authors utilized a greased fall cone of 76 g mass and 30° apex angle that was allowed to penetrate into the 7-d cured test specimens contained in 50 mm diameter by 30 mm high sample cups. For this set up, the authors defined the liquid limit w_L value as corresponding to h = 17 mm and purport to have followed the British Standard (BS) fall-cone test method (BSI 1990). However, the BS fall-cone test method specifies an 80g–30° cone, 55 mm diameter by 40 mm high sample cups, with the w_L value defined as the moisture content at which this cone penetrates a depth of 20 mm into remolded test specimens. Koester (1992) reported the use of a 76g–30° cone to determine w_L as the water content at 17 mm penetration of the said cone as being specified in the 1989 Chinese code. This procedure is used in MWRPRC (1999) (with a greased cone) which also recommends that plastic limit be taken at the moisture content where the cone penetrates 2mm. Further, the BSI (1990) approach does not involve coating the cone-tip surface with a thin layer of grease or lubricant, which would have the effect of altering the cone characteristics, significantly increasing the value of the cone factor (*K*) (as defined by Eq. (1)

in the paper under discussion) for the purposes of undrained shear strength determinations (Koumoto and Houlsby 2001), as elaborated in the next paragraph.

With different values of h assigned for the w_L condition as well as different fall-cone weight (W) and K values, these two fall-cone setups might produce different values of w_L for the same *remolded* test material. Ignoring the effect on the K value of greasing the cone, the undrained shear strength at the 'liquid limit' would have increased by a factor of approximately 1.31 owing to the lighter cone and lower penetration relative to the BS fall-cone setup. This would have an effect on the values of the liquid limit thus calculated. Could the authors clarify which testing standard or methodology was followed during the work?

Undrained shear strength values, measured using the fall-cone device, are as accurate as the cone factor (K) value used in any back-analysis to estimate a strength value. From Eq. (1), the value of K can be linked to the assumed undrained shear strength at liquid limit if this is associated with a specific value of penetration depth for a cone having particular weight and cone apex angle values (cf. Vardanega and Haigh 2014). In determining the fall-cone undrained shear strength, the authors employed a K value of 1.33 in applying the reported Eq. (1). Referring to their theoretical analysis of the fall-cone test, Koumoto and Houlsby (2001) calculated K values of 2.00, 1.33 and 1.03 for 30° fall cones with fully smooth (i.e. zero shear stress: $\alpha = 0$), partially rough ($\alpha = 0.5$) and fully rough ($\alpha = 1.0$) cone-tip surfaces, respectively: where α is the cone adhesion factor. In other words, as an initial observation, there is a discrepancy between the K value of the greased cone-tip surface used by the authors and the theoretical value for the equivalent smooth cone reported in Koumoto and Houlsby (2001).

In practice, however, experimentally derived K values (often calibrated against vane-shear undrained strength) are consistently lower than these theoretical K values. For instance, experimental K values for a 30° cone of either 0.8 or 1.0 were reported for (nominally) undisturbed clay samples in Hansbo (1957). An average K value of about 0.79 (for a 30° cone) from the work reported in Karlsson (1961) can be stated, noting that Koumoto and Houlsby (2001) point out that the actual K values reported in Karlsson (1961) are 'too low by a factor of 10.0'. Wood (1985) gives an average value of 0.85 for a 30° cone used to test some clayey soils. Only independent experimental strength measurements can validate fall-cone derived s_u values; such measurements were not reported by the authors in the paper under discussion. Consequently, all values of s_u quoted in the paper are as accurate as the K value assumed.

In the absence of calibration strength measurements, one approach is to examine the predicted fall-cone undrained strength value at the w_L which is generally understood as corresponding to an average value of 1.7 kPa (Wroth and Wood 1978). Using Eq. (1) and taking $K = 1.33$, the undrained shear strength value at the liquid limit value for the 76g–30° fall-cone setup (with $h = 17$ mm assigned at liquid limit) employed by the authors is predicted as 3.43 kPa. Also Eq. (1), as given in the paper, is said by the authors to have s_u in kilopascal and h in millimeters, but in reality it is s_u in Pascals and h in meters together with W (being the cone weight not mass) in Newtons. If one takes the undrained shear strength at liquid limit to be equal to 1.7 kPa instead, one can compute from Eq. (1) a revised value for K of 0.659 (about a factor of two smaller than the theoretical value of 1.33) for use in undrained shear strength calculations for the authors' fall-cone set up.

Determination of Plastic Limit

In using the reported Eq. (3) after Feng (2000) in their analysis, the authors employed a log–log representation of fall cone data (previously suggested by Kodikara et al. (1986, 2006), Feng (2000, 2004) and Chen et al. (2013)). Eq. (3) is constructed from Eq. (2) on the basis that $h = 2.0$ mm at the w_P value and $h = 20.0$ mm at the w_L value, with this factor of 10 difference when squared leading to the assumption of a 100-fold increase in the s_u value over the plastic range (e.g., Wroth and Wood 1978). Hence, with h = 17.0 mm assigned to the w_L for the authors' investigation, the w_P values reported in their paper are the moisture content values that produced approximately a 72 fold increase in the undrained shear strength deduced for their fall cone w_L values (i.e., corresponding to an s_u value of 3.43 × 72 ≈ 247kPa). For clarity, the discussers introduce the notation w_{P72} to identify their derived 'plastic limit' values.

While the assumption of a 100-fold increase in undrained shear strength over the plastic range is a soil mechanics fallacy (Haigh et al. 2013; O'Kelly 2013a), nevertheless, the designation of a strength-based plastic limit is potentially useful (Stone and Phan 1995; Haigh et al. 2013; O'Kelly et al. 2018) and in recent literature has been termed the plastic strength limit, w_{P100} (Haigh et al. 2013), to distinguish it from the international standard thread-rolling plastic limit after Atterberg (1911a, 1911b).

However, it is important to emphasize that any expected agreement between the $w_{P\,100}$ (or any similarly defined strength based plastic limit values) and the thread-rolling plastic limit values is purely coincidental (Haigh et al. 2013; Sivakumar et al. 2016; O'Kelly et al. 2018). The thread-rolling plastic limit corresponds to the remolded state, as emphasized earlier, whereas the values deduced in the authors' investigation are for 7 d cured soil specimens.

Referring to the values presented in Table 2; the authors observed that both w_L and w_P values of the 12% lignin-stabilized silty soil mixture are approximately 20% higher than those obtained for the natural silty soil (0% lignin content), or expressed in absolute terms as percentage point differences of 8.8% and 4.3% for w_L and w_P, respectively, with the deduced plasticity index increasing in value from 10.1% to 14.6% for the 0% and 12% lignin contents, respectively. Given the sizable amount of lignin additive, the reported values would suggest that the changes in the plastic range for increasing lignin content are considered markedly small. However, it is worth repeating that the w_L and w_P values deduced by the authors do not define the range of plasticity for the remolded materials (at least that defined by the BSI standard they quote), but define instead a range of moisture contents corresponding to h values of 17.0 and 2.0 mm, respectively, for the 7 d cured specimens tested using the authors' 76g–30° fall-cone setup.

Moisture content determination

For their moisture content determinations, the authors adopted an oven drying temperature (t) of 30°C, rather than the standard t range of 105±5°C (ASTM, 2014), to ensure the integrity of lignin during the oven-drying process, which is understandable. However, residual pore water remaining in the dried specimens for $t < 100$°C results in an underestimation of their actual moisture content value since it is included with the specimen dry masses for the purposes of performing the moisture content calculations (O'Kelly 2004; O'Kelly and Sivakumar 2014). The authors' adopted t value of 30°C is grossly below the ASTM oven-drying temperature range and the resulting effect is compounded in the cases of lignin-stabilized soils and other organic soils, including peats, since a sizable fraction of the free water is contained in the intra-aggregate pores (Locat et al. 1996; Horpibulsuk et al. 2004; O'Kelly and Pichan 2013).

In terms of $s_u - w$ correlations, the effect of employing lower values of t in performing the moisture content determinations is to translate the experimental $s_u - w$ correlation to the left, when presented in an s_u versus w plot, as demonstrated in O'Kelly (2014) and (O'Kelly and Sivakumar 2014) for different organic soils. For this reason, these researchers recommended a standardized $t = 105$°C for routine moisture content determinations on such materials, thereby allowing valid comparisons between experimental $s_u - w$ correlations proposed by different researchers and (or) different soil materials. Two experimental approaches are given in O'Kelly (2004, 2005) for comparison of w values measured for the same organic soil, based on the use of different t values.

Undrained shear strength variation with changes in moisture content

The authors give Eq. (5) in the paper to explain the variation in fall cone s_u with a liquidity index (I_L) parameter for the materials tested. Since the I_L parameter was computed on the basis of the values of w_L and w_{P72} deduced for the undisturbed 7-d cured lignin-stabilized soil specimens using the 76g–30° fall cone setup, it is different to the traditional liquidity index parameter, which is defined in terms of the fall cone or percussion cup w_L value and the thread rolling w_P value (see BSI 1990).

In Fig. 7, the authors compared their computed fall cone s_u values deduced for the 0–12% lignin-stabilized silty soil mixtures investigated with those values calculated from three $s_u - w$ correlations reported in the papers by Federico (1983), Berilgen et al. (2007) and Chen et al. (2013). It should be pointed out that one of these correlations was derived for remolded soil (Federico 1983) and a second for reconstituted soil (Berilgen et al. 2007). There are a myriad of other empirical correlations proposed to relate s_u with w, w_L or I_L, some of which are summarized and compared in O'Kelly (2013a). Based on comparisons of the relative performances of these three correlations in predicting their fall cone s_u values, the authors concluded that, in general, none of them could predict the fall cone s_u values of the 7 d cured lignin-stabilized silty soil mixtures very well, motivating them to propose their new $s_u - I_L$ relationship given by Eq. (5) in the paper under discussion.

Since the mobilized s_u value depends on the soil mineralogical composition and material characteristics, the strength measurement approach employed, the t value adopted for moisture content determinations on temperature-sensitive geomaterials, and the definitions and measurement approaches employed for w_L, w_P and I_L determinations (e.g., O'Kelly 2013b), it is not surprising that great variability often exists between s_u predictions made using various correlations proposed by different researchers. The empirical Eq. (5) proposed by the authors for estimating the fall cone s_u values relates specifically to the lignin-stabilized silty soil material investigated using the 76g–30° greased cone setup, with the w_P and w_L values defined for h = 2 and 17 mm, respectively, and the t value of 30°C employed for moisture content determinations. Caution is urged in applying Eq. (5) more widely for other lignin-stabilized soils and for geomaterials in general.

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Notation

The following symbols are used in this discussion:

h = fall cone penetration depth;

I_L = liquidity index

K = cone factor;

s_u = undrained shear strength;

t = oven drying temperature;

w = moisture content;

w_L = liquid limit;

w_P = plastic limit determined by the thread rolling method;

w_{P72} = plastic strength limit corresponding to a 72 fold increase in undrained shear strength from liquid to plastic limit;

w_{P100} = plastic strength limit corresponding to a 100 fold increase in undrained shear strength from liquid to plastic limit;

W = fall cone weight;

α = cone roughness factor.

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