

DISCUSSION

Discussion: The effect of surface roughness and shear rate during fall-cone calibration

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In their paper (Llano-Serna & Contreras, 2020), the authors provide valuable insights into the effects of surface roughness and shear rate during 30°, 80 g fall-cone calibration, investigating a standardised, smooth, polished cone (arithmetical mean roughness (R_a) value of 0.8 μm , i.e. compliant with ISO 17892-6 (CEN, 2017)) and two rougher cones with R_a values of 1.5 and 4.7 μm . The authors report that, for the investigated tailing, kaolin and sediment soils, the experimental result presented in Fig. 6 'seems counterintuitive and does not support a generally accepted concept ... the idea of the roughness as an important influencing factor on the cone mechanics' (Llano-Serna & Contreras, 2020; p. 338) from which they conclude that 'for the scale of the fall-cone test, roughness changes within the scale of variation analysed here ($R_a = 0.8\text{--}4.7\text{ }\mu\text{m}$) do not affect the fall-cone penetration considerably' (Llano-Serna & Contreras, 2020; p. 338). In this submission, the discussor makes two main contributions: (a) presentation of some experimental data in support of the above finding; (b) the significance of natural variation in the rate dependence parameter (μ) between different fine-grained soils on the determination of the cone factor, K .

For the same specimen preparation methods and testing procedures as those described in the paper under discussion, fall-cone and mini-vane shear tests were performed on a commercially available kaolin ($w_l = 59.3\%$, $w_p = 30.2\%$) for the purposes of this submission. Note that the consistency index values of this material (referred to as kaolin 2) are different from those reported for the kaolin investigated by the authors (90% and 36%, respectively) (referred to as kaolin 1), although this is not unexpected since these materials were obtained from different sources. For instance, a different kaolin material investigated by Sivakumar *et al.* (2015) had reported $w_l = 70\%$ and $w_p = 33.8\%$. Five 30°, 80 g cones were investigated – that is, a smooth polished one (denoted as FC1), compliant with CEN (2017), and four others manufactured using a lathe machine to have repetitive surface patterns of concentric grooves (see Fig. 10 and Table 6). The various surface patterns for the four manufactured cones, FC2–FC5, were created using a Quadcut carbide thread-cutting tool having a 60° point angle, employing the same depth of cut (amplitude) value of 0.10 mm, advancing the tool by the required amount using the top slide, with pitch (frequency) values ranging from 0.10 to 1.00 mm. In the case of cone FC2, the process

resulted in the tip of the next groove being removed for the smallest 0.10 mm pitch dimension investigated, such that the reduced amplitude (y_{max}) of its finished triangle wave pattern profile was calculated as 0.087 mm. For these profiles, the mathematical values of R_a (arithmetical mean deviation perpendicular to the grooves, which is the direction of motion during indentation) were calculated in the range 5.1–21.7 μm – that is, cones FC2–FC5 have greater roughness than the cones investigated by the authors. It is acknowledged that the repetitive surface patterns on the cones FC3–FC5 are not of real interest for fall-cone practices, but as described later, their results demonstrate that the sole use of the R_a parameter for roughness characterisations may not be always reliable. The vane-shear tests were performed in triplicate, with vane blades measuring 25.4 mm wide and 25.4 mm deep, and for a shearing angular velocity (ω) of 12°/min, following the recommendation from BS 1377-7 (BSI, 1990b).

Figure 11(a) presents for the kaolin 2 material the average cone penetration depth (h_d) obtained using cones FC1–FC5 at four altered water contents about the liquid limit condition (defined as $h_d = 20$ mm for the 30°, 80 g fall-cone set-up according to BSI (1990a)). Also included in this figure are the vane shear strength–water content data, from which the K values presented in Fig. 11(b) were calculated using the Hansbo (1957) fall-cone relationship (equation (6)). For example, considering cone FC1 ($R_a = 0.8\text{ }\mu\text{m}$), kaolin 2 produced a value of $w_l = 59.3\%$, with the corresponding vane shear strength interpolated as $s_{u(LL)} = 0.81$ kPa, giving a computed K value of 0.413. In the same manner, $w_l = 60.9\%$, $s_{u(LL)} = 0.78$ kPa and $K = 0.398$ were computed for cone FC2 ($R_a = 21.7\text{ }\mu\text{m}$) – that is, for the kaolin 2, the rough cone (FC2) had practically the same K value as the smooth, polished one (only 3.7% lower), in agreement with the authors' finding, but appeared to extend it for a considerably wider R_a range. Note, for the same ω value of 12°/min used in testing kaolin 2, the kaolin 1 material produced an $s_{u(LL)} \approx 0.52$ kPa (Fig. 7), which results in a computed K value of 0.27. As explained earlier, since these kaolin materials had different consistency indices, it would not be unexpected for them to have different strength parameter (K) values.

The authors postulated 'It may be possible that for larger grooves than those depicted in Figs 4 and 5; the roughness effect is substantial' (Llano-Serna & Contreras, 2020; p. 338). It is evident from the results presented for the kaolin 2 material in Fig. 11 that the larger (0.10 mm deep) grooves of the repeating surface patterns for cones FC3–FC5 produced higher values of $w_l = 62.6\text{--}63.6\%$ and lower $s_{u(LL)} = 0.72\text{--}0.74$ kPa compared to cones FC1 and FC2, supporting the authors' hypothesis. According to the theory and experimental observations, rougher cones have lower values of K for a given cone geometry (e.g. Koumoto & Houlsby (2001)). As is evident from Fig. 11(b), however, compared to cone FC2 ($R_a = 21.7\text{ }\mu\text{m}$ and $K = 0.398$), the computed K values for cones FC3–FC5 ranged from 0.367 to

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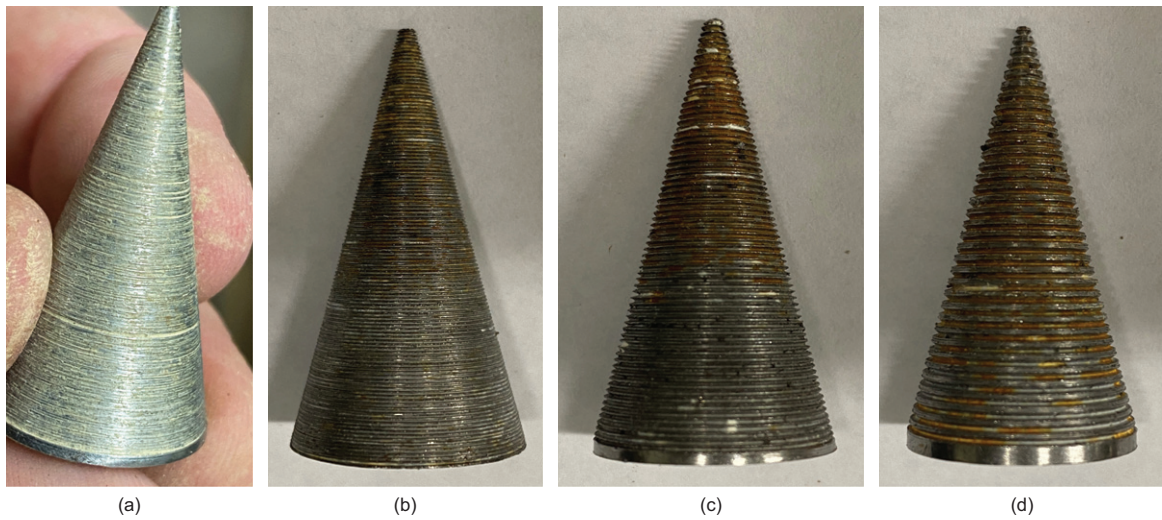


Fig. 10. Manufactured 30°, 80 g fall cones: (a) FC2; (b) FC3; (c) FC4; (d) FC5

0.377 (i.e. 5.1–7.7% lower) and, furthermore, exhibited a trend of marginally increasing K for increasing R_a . The latter phenomenon appears counterintuitive and inconsistent with fall-cone theory, but arise from the sole use of the R_a parameter for roughness characterisations, which is not always reliable. A combination of two roughness parameters is often recommended in surface metrology practice – that is, one related to amplitude and the other to frequency. For instance, compared to FC2 (21.7 μm), the cones FC3–FC5

Table 6. Manufactured 30°, 80 g fall cones with various surface patterns and roughness values investigated for the kaolin 2 material ($w_1 = 59.3\%$, $w_p = 30.2\%$)

Fall cone ID	Depth of cut, y_{\max} : mm	Pitch: mm	R_a : μm
FC2	0.087	0.10	21.7
FC3	0.10	0.30	11.8
FC4	0.10	0.50	8.9
FC5	0.10	1.00	5.1

have lower values of $R_a = 5.1$ – 11.8 μm , since although their grooves are deeper, they are also less frequent.

The second contribution point of this submission concerns the significance of natural variation in the μ parameter (variation in undrained shear strength, s_u , per tenfold increase in strain rate) between different fine-grained soils in relation to the experimental K value. Equation (5) shows a μ value of 0.1, typically associated with inorganic fine-grained soils. However, it is not uncommon for the rate of s_u increase to range between 0.05 and 0.15 (Ladd & Foott, 1974), and highly organic soils can have even greater μ values. For instance, the natural water-treatment residue (WTR) material fall-cone tested in accordance with the British standard by O'Kelly (2014), data for which is included in the Bayesian statistical approach analysis presented by the authors, had a measured μ value of 0.20 (O'Kelly, 2018). Further, in equation (2), $\zeta (s_u/s_{ud})$ indicates the changes in K induced by the rate of strain during cone penetration, with the tailing, kaolin 1 and sediment materials investigated by the authors noted to have a rather considerable variability in ζ (Figs 6(b)–6(d)), with reported mean ζ values of 0.48, 0.53

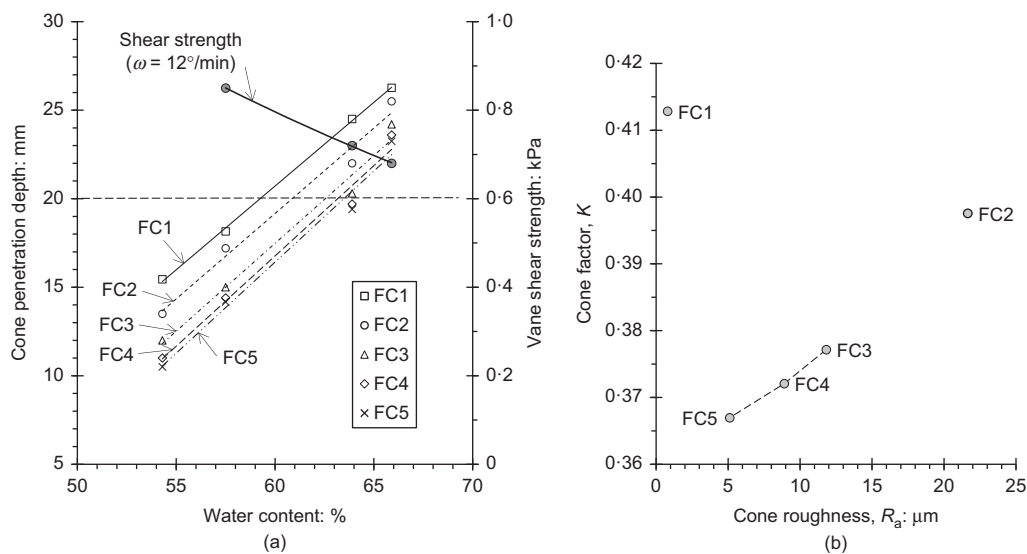


Fig. 11. Experimental results for the kaolin 2 material: (a) cone penetration depth and vane shear strength plotted against water content; (b) deduced cone factor plotted against cone surface roughness

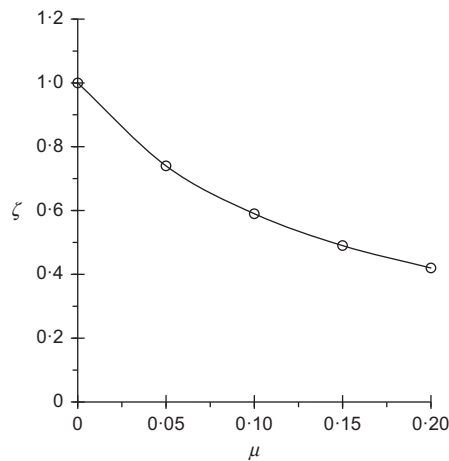


Fig. 12. Plot of ζ (s_u/s_{ud}) against the rate dependence parameter determined from numerical analysis of the fall-cone test (30° cone) by Hazell (2008)

and 0.43, respectively. As such, according to the correlation given in Fig. 12, these soils could have markedly different μ values. The authors state that ‘the resulting K using equation (6) and adopting different types of soils and several ω values should follow a linear trend in a semi-log plot similar to the one described by equation (5)’ (Llano-Serna & Contreras, 2020; p. 334), from which they introduce equation (7) used to interpret the calibration data supporting their work, arguing that ‘similarly to equation (5) ..., equation (7) should present a constant increase defined by KS ... and is valid for more than one soil type’ (Llano-Serna & Contreras, 2020; p. 334). The authors seem to be implying that best-fit linear trendlines to the data points for each of the kaolin 1, WTR and other soils investigated would be coincident in the semi-log plot. However, since these materials have considerably different experimental ζ (μ) parameter values, it is suggested that this would not be the case.

As a minor correction to the original paper, the citations to O’Kelly (2016) and O’Kelly *et al.* (2017) listed their wrong publication years – the correct references (O’Kelly, 2018; O’Kelly *et al.*, 2018) are included in the References section below.

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NOTATION

h_d	cone penetration depth
K	cone factor
KI	empirical model intercept
KS	empirical model slope
R_a	surface roughness
s_u	undrained shear strength
s_{ud}	dynamic undrained shear strength
$s_{u(LL)}$	vane shear strength at fall-cone liquid limit
w_l	liquid limit
w_p	plastic limit
ζ	ratio of static undrained strength to dynamic undrained strength
μ	rate dependence parameter
ω	shearing angular velocity

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