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DISCUSSION

The plastic limit of clays

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Contribution by G. E. Barnes

The authors have provided valuable insights into mechanisms that occur in the standard plastic limit test (Haigh *et al.*, 2013). The discusser wishes to make some further contributions to this interesting subject.

The discusser agrees with the authors that the diameter of the thread at the onset of the brittle state is not significant. There is an unfortunate perception that threads must crumble *at* 3 mm, reinforced by the use of the 3 mm diameter brass rod (BS1377:1990; BSI, 1990) and the description in ASTM D4318-10 (ASTM, 2010) of 3·2 mm as the 'proper diameter'. Prakash *et al.* (2009) showed that the water content at crumbling was virtually independent of the thread diameter and ASTM D4318-10 permits crumbling at diameters greater than 3·2 mm as a satisfactory end point, providing the soil was previously rolled to 3·2 mm.

From Terzaghi's definition 'the [lower] plastic limit represents the water content at which a soil ceases to be plastic, the term 'plastic' meaning merely the capacity of the soil to be rolled out into threads with a certain standard diameter' (Terzaghi, 1926). This 'certain standard diameter' simply defines a 'thin' thread. Earlier publications by Terzaghi (1925a, 1925b) support this view.

The plastic limit has been described as a test of ductility (Vaughan *et al.*, 1988) and of brittle failure (Schofield & Wroth, 1968) with the plastic limit being the water content at the ductile–brittle transition (Barnes, 2013a). The authors recognise that an alternative test would require the water content at the ductile–brittle transition to be identified. An apparatus has been developed by the discusser (Barnes, 2009, 2013a, 2013b) that replicates Atterberg's rolling procedure, determines a measure of toughness and identifies the ductile–brittle transition. Good linear relationships between toughness and water content are obtained from which new toughness properties are derived.

The discusser is in complete agreement with the authors about the strength fallacy and proposed this as a myth in soil mechanics (Atkinson, 2010; Barnes & O'Kelly, 2011). The introduction of a plastic strength limit PL_{100} and a supplementary plasticity index PI_{100} seems unnecessary.

The authors' approach to the critical state undrained shear strength assumes the triaxial compression shearing mode. The discusser contends that with rapid rolling the contact between the hand (or the plate of an apparatus) and the soil thread moves quickly around the thread and rather than applying a static line/strip load a quasi 'all-round' or 'rolling' radial pressure is applied that causes the thread to extrude and reduce in diameter uniformly in a triaxial extension mode. With equal major, σ_1, and intermediate, σ_2, radial principal stresses and the minor principal stress, σ_3, on the longitudinal axis assumed to be zero, the mean stress would be

$$p' = \frac{2\sigma_1}{3} - u \tag{8}$$

and with

$$q = \sigma_1 = Mp' \tag{9}$$

it can be shown that

$$2c_u = M\left(\frac{4}{3}c_u - u\right) \tag{10}$$

and

$$c_u = \left(\frac{3M}{6 - 4M}\right)(-u) \tag{11}$$

In the triaxial extension mode M is given by

$$M = \frac{6\sin\phi'}{3 + \sin\phi'} \tag{12}$$

Taking the range of ϕ'_{cv} values for montmorillonitic and kaolinitic clays as 10–20° and 25–35°, respectively (Toyota *et al.*, 2009), M values of 0·33–0·61 and 0·74–0·96 are obtained. Assuming the mean stress is given by the cavitation tensions of 100–400 kPa suggested by the authors, following Baker & Frydman (2009), higher strengths at the plastic limit are obtained for the kaolinitic clays, of about 73–540 kPa compared to montmorillonitic clays, of about 21–210 kPa. However, published data show that the undrained shear strength of kaolinitic soils at the plastic limit is usually less than that of montmorillonitic soils (Dumbleton & West, 1970; Black & Lister, 1978, 1979).

The authors report studies showing a wide range of undrained shear strengths at the plastic limit. Several researchers have also found a wide range of suctions at the plastic limit (Rollins & Davidson, 1960; Black, 1962; Dumbleton & West, 1970; McBride, 1989; also Marinho & Oliveira (2012) at the optimum water content) and effective stresses at the plastic limit (Carrier & Beckman, 1984; Nagaraj & DeGroot, 2004).

The authors consider that fracture failure in a soil thread below its plastic limit is the result of either cavitation or air entry. The results of Cafaro (2002) and Marinho & Oliveira (2012) illustrate that the desaturation point lies close to the plastic limit. However, there is considerable evidence that the soil fabric and the mechanisms of aggregate development and crack propagation are also involved in brittle failure.

Compacted soil fabric is usually referred to as matrix dominated microstructure wet of the compaction optimum and aggregated macrostructure dry of optimum, for example, Gens *et al.* (1995), Vanapalli *et al.* (1999), although Delage *et al.* (1996) refer to this structural rearrangement occurring each side of the plastic limit. At the plastic limit, wet of optimum (Gurtug & Sridharan, 2004; Marinho & Oliveira, 2012), the soil crumbles as a result of its aggregated and cracked state. Aggregation close to the plastic limit in the

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uncompacted state is demonstrated by Tarantino and De Col (Tarantino *et al.*, 2009).

For soils wet of the plastic limit, a proportion of large pores has been detected by mercury intrusion porosimetry (MIP) (Juang & Holtz, 1986; Prapaharan *et al.*, 1991; Gens *et al.*, 1995; Simms & Yanful, 2004) with an inter-aggregate porosity identified (Tarantino & De Col, 2008; Tarantino *et al.*, 2009). Simms & Yanful (2004) described a network of elongated microcracks in a clay till compacted wet of the plastic limit and suggested that larger pores, not detected by MIP, could exist depending on the degree of compaction.

At the plastic limit, with soil in a relatively uncompacted state, large pore spaces will provide defects that can be aggravated by fluctuating internal compressive and, especially, tensile stresses during rolling of the soil thread, compounded by changes in the pore air and water pressures weakening the structural stability around the pores and promoting crack propagation through extension and interconnection with ultimately separation of the aggregates when the thread collapses.

Authors' reply

The authors would like to thank the discusser for his interest in their paper and for his contributions on the mechanisms taking place within the plastic limit test.

PLASTIC STRENGTH INDEX

The discusser asserts that the introduction of a plastic strength index indicating the water content required to change the strength of soil by some multiple of that at liquid limit (as initially proposed by Stone & Phan (1995)), is unnecessary. This, however, depends on the purpose for which a plasticity index is required.

Liquidity index (I_L) is often used to estimate the strength of a soil at a given water content following the general formulation given in Wroth & Wood (1978) and Wood (1990), based on the assumption of a ratio $R_{MW} = 100$ between undrained strengths at plastic and liquid limits and a linear relationship between the logarithm of undrained strength and water content.

$$c_u = c_L R_{MW}^{(1-I_L)} \tag{13}$$

where c_L is the value of undrained shear strength at the liquid limit (usually 1·7 kPa following the work of Wroth & Wood (1978)). The adoption of $R_{MW} = 100$ followed the original assumption made in Schofield & Wroth (1968) (based on vane shear strength test data from Skempton & Northey (1953) on four soils).

Vardanega & Haigh (2014) assembled a database of 641 fall cone tests on 101 soils and have demonstrated that in the range of $0{\cdot}2 < I_L < 1{\cdot}1$ an average value of 35 is more reasonable for the R_{MW} parameter. However, it should be noted, that few data were available at liquidity index values lower than 0·2.

$$c_u = c_L 35^{(1-I_L)} \quad 0.2 < I_L < 1.1 \tag{14}$$

Incidentally in Vardanega & Haigh (2014) the use of logarithmic liquidity index (I_{LN}) (Koumoto & Houlsby, 2001) is also studied and the following formulation is produced:

$$c_u = c_L 83.5^{(1-I_{LN})} \quad 0.2 < I_L < 1.1 \tag{15}$$

While both equations (14) and (15) are statistically significant, it could be argued that these correlations would improve if a plastic limit value based on a strength criterion were available rather than the current one based on ductility.

STRESS STATE

The authors disagree with the discusser that the rolling of a thread in the plastic limit test corresponds to triaxial extension with equal stresses applied around the circumference of the thread. Despite the constant rolling of the thread, the stress is only ever applied in one axis at any given time and the stress state is thus more analogous to triaxial compression, as stated in the original paper.

INFLUENCE OF MINERALOGY

While the discusser states that the undrained shear strength of kaolinitic soils at plastic limit is usually less than that of montmorillonitic ones, the data cited from Dumbleton & West (1970) (also discussed by Black & Lister, 1978, 1979) include data only for samples of pure kaolinite and montmorillonite mixed with varying amounts of sand. These artificial soils may not fully reflect the behaviour of natural soils, especially as the high sand fractions may promote air entry at the plastic limit. The analysis of the database of fall-cone test data presented in Vardanega & Haigh (2014) did not reveal any clear link between the R_{MW} value and soil mineralogy.

Mineralogy will affect the microstructure of the clay and hence may also affect the suctions at which cavitation or air entry will occur. The range of cavitation suctions of 100–400 kPa suggested by Baker & Frydman (2009) ignores any effect of mineralogy on these numbers; higher values within this range may possibly be associated with pure bentonites which seem to show high strengths at plastic limit.

SOIL FABRIC

The discusser concludes with a discussion of the effects of soil fabric on the cracking of soil. Most of this discussion is based on the fabric of compacted soil samples wet of optimum. In the plastic limit test the sample is remoulded and compressed by internal suction, rather than being dynamically compacted, and will thus not show the same structure. Crack propagation is obviously the mechanism of failure in the plastic limit test, but the mechanism of initiation of this crack will differ from that in a compacted soil. While the internal fabric of the soil sample is clearly important, the absence of air voids within the plastic limit test sample requires a different crack initiator. It is the authors' postulation that this crack is initiated either by air entry or by cavitation, this being in agreement with the general range of strengths observed at plastic limit.

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