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Particle breakage and the critical state of sand

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Abstract

Soil particles break during shear, with the intensity of the breakage depending on the stress level amongst other factors. Particle breakage has important implications for the soil's critical state, which is an input to the majority of advanced constitutive models. This work examines a micromechanical framework where particle breakage shifts down the critical state locus in void ratio versus mean effective stress space without changing its slope. The framework assumes that detectable particle breakage in sand does not occur unless the contraction potential of the material, solely by the sliding and the rolling of the particles, is exhausted and a soil specific stress level threshold is surpassed. A series of triaxial compression tests conducted to investigate the validity of the framework is presented. It is shown that particle breakage is a factor, working alongside dilatancy, imposing additional compressibility on the soil.

Keywords: Particle breakage; Particle crushing; Critical state; Sand; Compressibility; Constitutive relations; Deformation; State parameter

1. Introduction

In critical state soil mechanics, shearing drives particulate soils towards a state of constant volume and constant shear stress at a constant mean effective stress, termed the *critical state* (Roscoe et al., 1958). At high stress levels, however, particles undergo breakage that results in a continuous change of soil gradation. The breakage causes additional compressibility and volume change, resulting in uncertainty in defining the critical state condition. In practice, stress levels sufficient for particle breakage occur in deep penetration problems, such as pile driving and cone penetration testing (Russell and Khalili, 2002), as well as below large earth-fill dams. Grain crushing has also been related to sanding in oil wells (Marketos and Bolton, 2007). Hence, the effect of particle breakage becomes important for understanding and analysing such problems within the critical state framework.

Traditionally, a two- or three-segment linear Critical State Locus (CSL) in $e - \log p'$ space (where e is the void ratio and p' is the mean effective stress), similar to the one shown in Fig. 1, has been adopted for the full range of p'. This is consistent with the three zones of behaviour identified by Vesić and Clough (1968): very low stress where dilatancy controls behaviour and breakage is negligible; elevated stress where breakage becomes more pronounced and suppresses dilatancy effects; and very high stress where the effects of

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Nomenclature

D_{50}, D_{10}	grain size larger than 50% and 10% (by mass) of the soil particles, respectively
e	void ratio
e_c	critical state void ratio
e_{min}, e_{max}	minimum and maximum void ratios, respectively
FC	fines content
G_s	specific gravity
p'	mean effective stress $(\sigma_1+\sigma_2+\sigma_3)/3$
q	deviator stress in triaxial compression, $\sigma_1 - \sigma_3$
u	pore pressure
Δ	denotes the increment of a variable
Δe_b	increment (reduction) of void ratio due to particle breakage
Δe_{sr}	increment of void ratio caused by sliding and rolling
ε_1	axial strain
ε_v	volumetric strain, $\varepsilon_1+\varepsilon_2+\varepsilon_3$
Γ	intercept of CSL in $e - \log p'$ space measured at $p'=1$ kPa
λ_{10}	slope of CSL in $e - \log_{10}(p')$ space
ψ	state parameter, $e - e_c$
ψ_0	initial state parameter, $e_0 - e_c$

initial density vanish, very little void space remains within the material, and soil behaves like an elastic material.

Difficulties are encountered with the three-segment CSL when considering particle breakage; these can be illustrated using the state parameter concept (Been and Jefferies, 1985). The evolution of the state parameter towards the three-segment CSL becomes logically questionable for stress paths that undergo a reduction in p' from a positive initial state. For the test shown in Fig. 1, the specimen starts at an initial state parameter, ψ_0, which is defined as the difference between the initial void ratio and the CSL void ratio at the same initial p'. If that specimen is now taken to the critical state, for example, under undrained conditions, then the implication is that the specimen has gone from a condition associated with a certain amount of breakage (since it is at a stress level within the second segment of the CSL), to one with less, or no, breakage (i.e., to the first segment of the CSL). This contradicts the fact that breakage is an entropic phenomenon which, of course, cannot be reversed by further shearing.

The elevated stress range (typically about 1 MPa $< p' <$ 30 MPa associated with the second segment of the CSL in Fig. 1), which covers the higher end of effective stress of interest in most geotechnical problems, has been less studied. To date, there is no consensus on whether a unique CSL exists for this

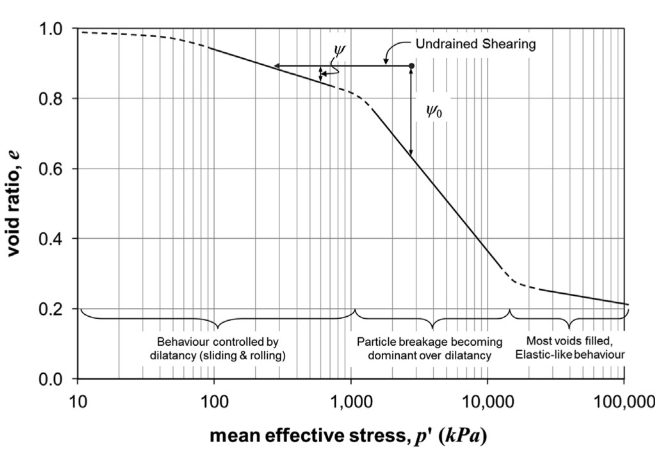

Fig. 1. Full stress range CSL in e–$\log p'$ space and a schematic undrained triaxial test.

stress range or on how it is affected by the continuous gradation change due to particle breakage. This work focuses on the critical state at the lower end of the elevated stress range (1 MPa $< p' <$ 3 MPa) where breakage gradually becomes dominant over dilatancy.

It is well accepted that shearing at high stress changes the gradation of a soil and facilitates volumetric compression (e.g., Lee and Farhoomand, 1967). The critical state is associated with a state of constant volume despite continued shearing. Hence, it is expected that for the soil to reach the critical state, a stable gradation should be reached for a specific stress level (Luzzani and Coop, 2002). This implies that such gradation would be more stable than the original one, and can sustain a higher level of stress without further breakage (despite being formed by particles of exactly the same mineralogical combination). Hypothetically this is a viable proposition, knowing that particle breakage drives the soil towards a less uniformly graded distribution and smaller particles, which will establish more inter-particle contacts (Bishop, 1966) and reduce the particle–particle contact forces for a given global stress. However, experimental evidence demonstrating the formation of a stable gradation related to a particular stress level is not yet available.

Been et al. (1991), Konrad (1998), Russell and Khalili (2004), and Vilhar et al. (2013) adopted the three-segment CSL framework illustrated in Fig. 1 and assumed that a continual constant volume state will be achieved once the tests approach the second segment of the CSL. The data presented by Russell and Khalili (2004) suggest that for elevated stress levels (above 1 MPa), tests on loose specimens do not reach a constant volume and continue to contract. Lade and Yamamuro (1996) made the same observation on tests presented in Yamamuro and Lade (1996), and concluded that the critical state conditions can only be achieved at very low stress (the first segment of CSL) or at very high stress after particle breakage has ceased (the third segment of CSL). Both sets of experiments were limited by the levels of shear strain allowed by the triaxial apparatus (up to around 40%). At lower confining stress, loose specimens often reach the critical state at such strain levels.

An experimental study on a granitic soil by Lee and Coop (1995) suggested that the amount of particle breakage at the