Engineering Geology 169 (2014) 61–68

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

A method proposed for the assessment of failure envelopes of cemented sandy soils

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ARTICLE INFO

Article history:
Received 15 July 2013
Received in revised form 31 October 2013
Accepted 27 November 2013
Available online 5 December 2013

Keywords:
Failure envelope
Shear strength parameters
Cemented sand
Triaxial tests
Unconfined compressive strength
Splitting tensile strength

ABSTRACT

This study aims at quantifying the influence of the amount of cement (C), the porosity (η) and the porosity/cement ratio (η/C_{iv}) in the assessment of the Mohr–Coulomb failure envelope of artificially cemented sands centered on splitting tensile strength (σ_t) and unconfined compressive strength (σ_c). Based on the concept previously established by Consoli et al. that the σ_t/σ_u relationship is unique for each specific sandy soil and cement agent, it is shown that the effective angle of shearing resistance of a given cemented sandy soil (Ø′) is independent of the porosity and the amount of cement of the specimen and that effective cohesion intercept (c′) is a direct function of the unconfined compressive strength (σ_c) [or splitting tensile strength (σ_t)] of the improved granular material, which depends on the porosity/cement ratio (η/C_{iv}) of the soil–cement blends. These concepts are tested with success for a uniform fine sand treated with early strength Portland cement and a silty sand treated with ordinary Portland cement, considering weak, moderate and strong cementation levels, as well as for a volcaniclastic formation deposit composed of moderately cemented fine sand and silt-size particles (naturally cemented soil). The methodology developed herein allows estimating c′ and Ø′ for any specific condition comprised inside the range of porosity and amount of cement employed during basic testing, without the necessity of carrying out triaxial testing or any other complex and time consuming tests.

1. Introduction

Portland cement at treatment levels of 3 to 10 percent by dry weight is particularly well-suited for low plasticity and sandy soils (Mitchell, 1981). Also according to Mitchell (1981) ranges of properties for cement treated granular soils are: density ranging from 14 to 22 kN/m^3, unconfined compressive strength (in kPa) ranging from 500 to 1000 of the cement content (in percentage by dry weight) and tensile strength varies from 0.20 to 0.33 of unconfined compressive strength.

Determination of Mohr–Coulomb failure envelope parameters of artificially cemented soils requires carrying out triaxial tests (*e.g.*, Consoli et al., 2000, 2007, 2012a; Dalla Rosa et al., 2008), simple shear (Festugato et al., 2013), amongst many other complex and time consuming tests. Mitchell (1981) suggested that friction angle of treated granular soils varies from 40° to 45° while Brown (1996) proposes values varying from 40° to 60°. Regarding cohesion intercept, Brown (1996) establishes that its value may be as high as a few thousand kPa, while Mitchell (1981) suggests that cohesion (in kPa) can be estimated as 0.225 times unconfined compressive strength (in kPa) plus 50 kPa. An alternative methodology to estimate Mohr–Coulomb failure envelope parameters of artificially cemented soils is suggested in present work. The concept is to carry out basic tests, such as unconfined compression and splitting tensile tests, which are available in any laboratory facilities (loading machine and proving rings). Besides, the methodology to be presented herein intends to allow increasing reliability and widening range of validity of the results, once the setup of basic (splitting tensile and unconfined compression) tests carried out for a given sandy soil and a specific cement agent will allow assessing c′ and ϕ′ for any specific condition provided that blends are inside the range of porosity and amount of cement tested.

2. The methodology proposed

The Mohr–Coulomb failure theory is represented in the shear strength (τ) versus effective normal stress (σ′) space by plotting Mohr semi-circles representing stress states at failure and then drawing a tangent to these semi-circles, which represents the Mohr–Coulomb failure envelope. As presented in Fig. 1, in the Mohr–Coulomb failure theory, the shear strength (τ) of a given material is assumed, considering effective stress conditions, to vary linearly with effective normal stress (σ′), according to two parameters: effective cohesion intercept (c′) and effective angle of shearing resistance (ϕ′), as shown in Eq. (1).

$$\tau = c' + \sigma' \tan\phi' \quad (1)$$

Using unconfined compression and splitting tensile tests principal stress states at failure, in which the minimum effective principal stress (σ_3') and maximum effective principal stress (σ_1') are $\sigma_{3c}' =$ zero and $\sigma_{3c}' = \sigma_c$ for unconfined compression and $\sigma_{3t}' = \sigma_t$ and $\sigma_{1t}' = -3\sigma_t$

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http://dx.doi.org/10.1016/j.enggeo.2013.11.016

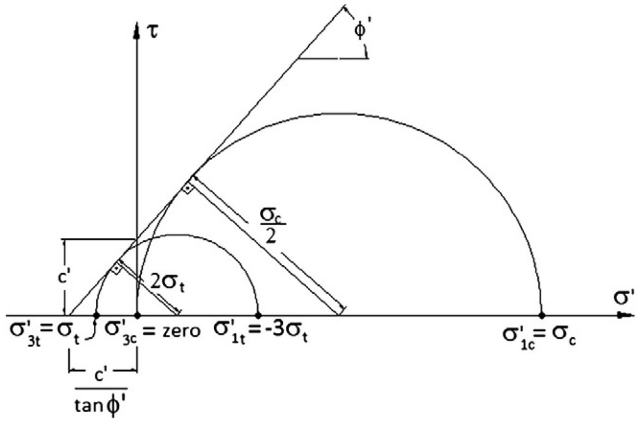

Fig. 1. Mohr–Coulomb envelope based on Mohr circles from splitting tensile and unconfined compression tests.

(Jaeger et al. 2007) for splitting tensile tests, it is possible to establish the following equations, based on triangle–rectangle shown in Fig. 1, respectively for unconfined compression (Eq. (2)) and splitting tensile [Eq. (3)] test results.

$$\sin\phi' = \frac{\frac{\sigma_c}{2}}{\left(\frac{\sigma_c}{2} + \frac{c'}{\tan\phi'}\right)} \quad (2)$$

$$\sin\phi' = \frac{2\sigma_t}{\left(\sigma_t + \frac{c'}{\tan\phi'}\right)} \quad (3)$$

Substituting $[c'/(\tan\phi')]$ of Eq. (2) into Eq. (3) and rearranging it in terms of $(\sin\phi')$ ends up in Eq. (4)

$$\sin\phi' = \frac{\sigma_c - 4\sigma_t}{\sigma_c - 2\sigma_t} \quad (4)$$

and consequently

$$\phi' = \arcsin\left(\frac{\sigma_c - 4\sigma_t}{\sigma_c - 2\sigma_t}\right) \quad (5)$$

Following, substituting ϕ' of Eq. (5) into Eq. (2) and rearranging it in terms of c' ends up in Eq. (6).

$$c' = \frac{\sigma_c\left[1 - \left(\frac{\sigma_c - 4\sigma_t}{\sigma_c - 2\sigma_t}\right)\right]}{2\cos\left[\arcsin\left(\frac{\sigma_c - 4\sigma_t}{\sigma_c - 2\sigma_t}\right)\right]} \quad (6)$$

In the development of a rational dosage methodology for soil-Portland cement, Consoli et al. (2010) have shown that the porosity/cement ratio (η/C_{iv}), defined as the porosity of the compacted mixture divided by the volumetric cement content, is an appropriate parameter to evaluate the unconfined compressive strength (σ_c) and the splitting tensile strength (σ_t) of Osorio sand–cement mixture, considering the whole range of cement content and the porosity studied. The σ_t/σ_c ratio was shown to be a scalar for the sand–cement mixture studied, being independent of porosity/cement ratio. As a consequence, dosage methodologies based on rational criteria can concentrate either on tensile or compression tests, once they are interdependable. Further studies by Consoli et al. (2012b, 2013) have corroborated that the σ_t/σ_c ratio was also a scalar for other soils and cementing agents, such as silt–lime and non-plastic clayey sand–cement blends. In the bases of these evidences, it is proposed herein that $\sigma_t = \xi\,\sigma_c$, where ξ is a scalar introduced into Eqs. (5) and (6), ending in ϕ' and c' being expressed by Eqs. (7) and (8).

$$\phi' = \arcsin\left(\frac{1-4\xi}{1-2\xi}\right) \quad (7)$$

$$c' = \frac{\sigma_c\left[1 - \left(\frac{1-4\xi}{1-2\xi}\right)\right]}{2\cos\left[\arcsin\left(\frac{1-4\xi}{1-2\xi}\right)\right]} \quad (8)$$

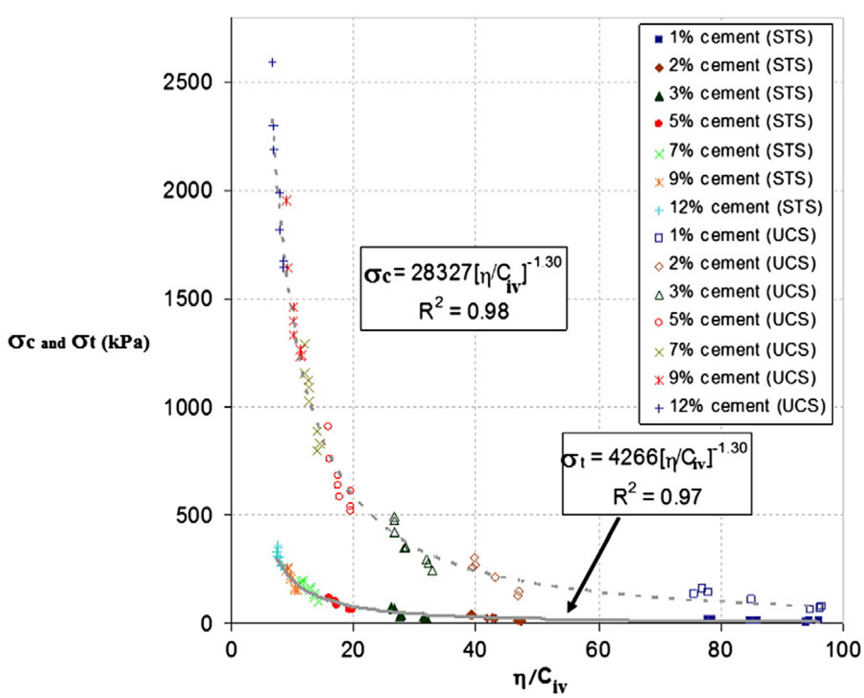

Fig. 2. Variation of unconfined compressive strength (σ_c) and splitting tensile strength (σ_t) with porosity/cement ratio (η/C_{iv}) [adapted from Consoli et al. (2010)].