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Modelling tensile/compressive strength ratio of artificially cemented clean sand

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Abstract

The present work proposes a new theoretical model for predicting both the splitting tensile strength (q_t) and the compressive strength (q_u) of artificially cemented sand and assesses their ratio for a given material. The proposed model is based on the concept of the superposition of the failure strength contributions of the sand and cement phases. The sand matrix obeys the concept of critical state soil mechanics, while the strength of the cemented phase can be described using the Drucker-Prager failure criterion. The analytical solutions are compared against the results of tests on three different types of cemented clean sand cured for different time periods. While the analytical relation fits the experimental data well, it also provides a theoretical basis for the explanation of some features related to the experimentally derived strength relationships for cemented clean sand. The value of the power relationship between the strength and the porosity/cement ratio index seems to be governed by the soil matrix properties, while the interdependency of the strength and the curing time can also be captured. For a given cemented sand, the model equally confirms the existence of a unique tensile/compressive strength ratio (q_t/q_u), independent of the curing time and primarily governed by the compressive to tensile strength ratio (or the friction properties) of the cement. It is also confirmed that the q_t/q_u ratio changes within a narrow range for different frictional properties of the cementing phase.
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Keywords: Modelling; Sands; Portland cement; Tensile strength; Compressive strength; Porosity/cement ratio

1. Introduction

Improving the mechanical characteristics of soil by mixing it with small amounts of binding agents, such as cement, is employed worldwide to foster the reuse of locally available soil and to decrease construction costs. The main purpose of this ground improvement technique is to reproduce the stable internal structure of naturally cemented or weakly bonded soil, resulting in an increased stiffness and peak frictional strength (e.g., Saxena and Lastrico, 1978; Dupas and Pecker, 1979; Clough et al., 1981) as well as the development of some tensile strength (e.g., Leroueil and Vaughan, 1990; Clough et al., 1981). These mechanical improvements generally come at the limited expense of a pronounced post-peak brittleness (e.g., Abdulla and Kiousis, 1997a; Wang and Leung, 2008) caused by the breakage of the artificial cementing bonds during loading.

The addition of cementing agents, especially Portland cement, has been widely adopted in many geotechnical applications to control excessive displacements or settlements of shallow foundations, to protect the slopes of earth dams and to prevent the liquefaction of loose granular soil in the subgrades and base courses of roads and airfields (e.g., Saxena et al., 1988; Porbaha et al., 1998;

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Nomenclature

a	parameter linking peak strength to state parameter	q_u	unconfined compressive strength of cemented sand
b_c	cohesion of cement phase	X	multiplying parameter in empirical relationship (1)
C_{iv}	volumetric cement content (expressed in percentage)	Y	multiplying parameter in empirical relationship (2)
M	critical state strength ratio for sand in t-s stress plane	Z	exponent of empirical relationships (1) and (2)
M_c	slope of failure line for cement phase in t_c-s_c plane	β	uniaxial compression and extension cement strength ratio
M^*	peak strength ratio for sand in t-s stress plane	ε	strain for cemented sand
k_u	composite stress ratio at failure for unconfined compression test	ε_c	strain for cemented sand
k_t	composite stress ratio at failure splitting tensile test	ϕ	friction angle for sand matrix
K_u	cement stress ratio at failure for unconfined compression test	ϕ_c	friction angle for cement phase
K_t	cement stress ratio at failure splitting tensile test	v	Poisson's ratio for cemented sand
s	mean stress of cemented sand	v_c	Poisson's ratio for cement phase
s_c	mean stress of cement phase	μ_c	concentration of volumetric cement
s_m	mean stress of sand matrix	μ_m	concentration of volumetric sand matrix
t	maximum shear stress of cement sand	σ_c^c	uniaxial compressive strength of cementing phase
t_c	maximum shear stress of cement phase	σ_c^t	tensile strength of cementing phase
t_m	maximum shear stress of sand matrix	ψ	state parameter
q_t	unconfined compressive strength of cemented sand	η	porosity
		η_{cs}	porosity at critical state

Gallagher and Mitchell, 2002; Thomé et al., 2005; Mitrani and Madabhushi, 2010). The technique seems particularly beneficial when the mixture is applied as a compacted stratum on top of weak soil layers (Consoli et al., 2009a). Consoli et al. (2009a) have shown that the failure mechanism of the top layers of cemented sand, vertically loaded with plates, is triggered once the tensile stress at the bottom of the top layer reaches the tensile resistance of the material. Faro et al. (2015) have shown that cement-treated sand layers built around the top of laterally loaded piles collapse due to the development of excessive compressive stress. All the above-mentioned geotechnical applications have a low confining stress level in common and, in these situations, the compressive and tensile strength characterisation of the cemented soil from unconfined compression and splitting tensile tests can offer relevant data for the appropriate design of cement-soil mixtures (e.g., Gomez and Anderson, 2012).

Possible dosage methodologies for sand-cement blends must consider the effect of distinctive variables (e.g., quantity of cement and porosity). Based on laboratory experiments, Consoli et al. (2009b) found an index named the porosity/cement ratio (η/C_{iv}) that, when plotted against the unconfined compressive strength (q_u), defines a power relationship for a given clean sand and a type of Portland cement under unsaturated conditions (i.e., low moisture contents in which pores of the sample are not predominantly filled with water during fabrication (Consoli et al., 2009c)), as follows:

$$q_u = X\left[\frac{\eta}{C_{iv}}\right]^Z \quad (1)$$

where porosity (η) is expressed as a percentage of the volume of voids divided by the total volume of the specimen, while the volumetric cement content (C_{iv}) is expressed as a percentage of the volume of cement divided by the total volume of the specimen. X and Z are material parameters that depend on the type of sand and the type of binder. In this approach, the changes in volume during curing are ignored. Consoli et al. (2010) have experimentally extended and confirmed the usefulness of such an index in controlling the splitting tensile strength (q_t) of artificially cemented sand. They employed the same sand and Portland cement as used in previous research, and the following power relationship with a similar shape was obtained:

$$q_t = Y\left[\frac{\eta}{C_{iv}}\right]^Z \quad (2)$$

where Z appears to retain the same value as for the compressive case (1), while the Y parameter shows a distinct value from X. In order to check if a q_t/q_u relationship

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