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Effects of coarse-grained material on hydraulic properties and shear strength of top soil

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ABSTRACT

Sidewalk failures associated with top soil of low shear strength are a common problem in urban areas. Mixing top soil with granite chips can be used to increase its permeability and shear strength. The effects of mixing granite chips with top soils on the hydraulic properties and shear strength under saturated and unsaturated conditions were investigated in this study. The results showed that the mixing top soils with granite chips caused changes in several key parameters of the soil–water characteristic curve (e.g., the air-entry value, the residual matric suction, and the residual volumetric water content) and the unsaturated permeability of the top soils. The saturated permeability and shear strength of the soil mixture increased with increasing content of granite chips.

1. Introduction

The island of Singapore consists mainly of three rock formations: (a) the Bukit Timah formation; (b) the Jurong formation; and (c) the Old Alluvium (Public Works Department, 1976; Pitts, 1984a,b; Leong et al., 2002). The Bukit Timah formation is a lower to middle Triassic intrusion and consists of granitic igneous rocks. The Jurong formation consists of a series of sedimentary rocks (e.g., sandstone, mudstone, shale, tuff, conglomerate and limestone) formed in the late Triassic to early Jurassic period. The Old Alluvium is a quaternary alluvial deposit of the ancient river system in the eastern part of Singapore and it consists mainly of clayey quartzo-feldspathic medium-grained sands and fine-grained gravels with some coarser gravels and lenses of silt and clay. High temperature and large precipitation provide optimum conditions for the rapid in-situ chemical and mechanical weathering of the Bukit Timah and the Jurong formations. As a result, thick residual soil profiles develop and cover almost two-thirds of Singapore's land area.

The residual soil is often mixed with organic materials to form top soil, which is commonly used as a medium for tree growth. In urban areas, the top soil is often added to the tree pits adjacent to sidewalks, which are generally well compacted and have high bearing capacity. The abundance of top soil in the tree pits, however, often causes sidewalks to experience differential settlements. This is due to the fact that top soil is often not compacted and also has low permeability and shear strength. The low permeability of the top soil will cause the area around sidewalks to have poor drainage. The water clogged in the soil reduces its shear strength and consequently induces sidewalk damage. In order to improve permeability and shear strength, top soil can be mixed with a coarse-grained material, such as granite chips. The soil mixture can be used as a planting medium and it also provides a high bearing capacity.

The concept of soil mixing using coarse-grained materials has received increasing attention as an alternative method for improving fine-grained soils. A number of research studies have been conducted to investigate the effects of soil mixing on the index properties (e.g., void ratio and dry density), saturated permeability, and shrink–swell potential of transported soils (e.g., Holtz and Lowitz, 1957; Holtz, 1985; Shakoor and Cook, 1990; Shelley and Daniel, 1993). Indrawan et al. (2006) investigated the effects of soil mixing on the hydraulic properties and shrinkage characteristics of

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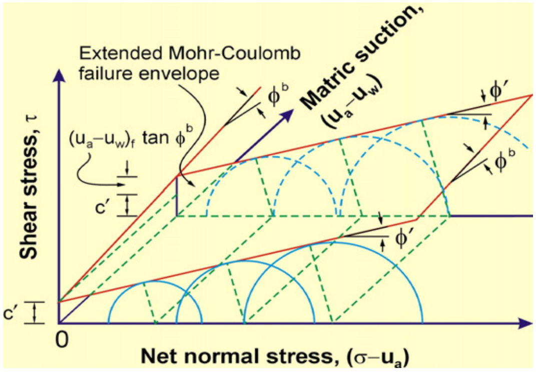

Fig. 1. Extended Mohr–Coulomb failure envelope for unsaturated soils (Fredlund and Rahardjo, 1993).

a local residual soil under unsaturated conditions. The effects of coarse-grained content on the shear strength of soil mixtures under saturated conditions have been investigated by several researchers (e.g., Miller and Sower, 1957; Holtz and Ellis, 1961; Patwardhan et al., 1970; Vallejo and Zhou, 1994; Vallejo and Mawby, 2000; Jafari and Shafiee, 2004; and Bergado et al., 2005). However, the effects of soil mixing on the hydraulic and shear strength properties of soil mixtures under unsaturated conditions have not been investigated and this is the objective of this paper.

2. Theory

The shear strength of a saturated soil is usually described using the Mohr–Coulomb failure criterion and the effective stress concept (Terzaghi, 1936), as follows:

$$\tau_{ff} = c' + (\sigma_f - u_w)_f \tan\phi' \quad (1)$$

where:

τ_{ff} shear stress on the failure plane at failure (kPa),
c' effective cohesion, which is the shear strength intercept when the effective normal stress is equal to zero (kPa),
$(\sigma_f - u_w)_f$ effective normal stress on the failure plane at failure (kPa),
σ_{ff} total normal stress on the failure plane at failure (kPa),
u_{wf} pore-water pressure at failure (kPa),
ϕ' effective angle of internal friction (°).

Table 1
Basic properties of the soils

Soils	Properties				
	Group symbol (USCS)	Group name	Specific gravity	Void ratio	Dry density (Mg/m^3)
TS	SC	Clayey sand	2.41	0.55	1.55
50GC–50TS	SC	Clayey sand with gravel	2.56	0.5	1.73
80GC–20TS	GP–GC	Poorly graded gravel with clay and sand	2.59	0.36	1.98
GC	GP	Poorly graded gravel	2.69	0.64	1.65

The shear strength of an unsaturated soil is given as an "extended" Mohr–Coulomb failure envelope as follows (Fredlund et al., 1978):

$$\tau_{ff} = c' + (\sigma_f - u_a)_f \tan\phi' + (u_a - u_w)_f \tan\phi^b \quad (2)$$

where:

τ_{ff} shear stress on the failure plane at failure (kPa),
c' intercept of the "extended" Mohr–Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction at failure are equal to zero; it is also referred to as "effective cohesion" (kPa),
$(\sigma_f - u_a)_f$ net normal stress on the failure plane at failure (kPa),
u_{af} pore-air pressure on the failure plane at failure (kPa),
ϕ' angle of internal friction associated with the net normal stress state variable, $(\sigma_f - u_a)_f$ (°),
$(u_a - u_w)_f$ matric suction on the failure plane at failure (kPa),
ϕ^b angle indicating the rate of increase in shear strength relative to the matric suction, $(u_a - u_w)_f$ (°).

The Mohr–Coulomb circles corresponding to failure conditions of an unsaturated soil can be plotted in a three-dimensional manner, as shown in Fig. 1. The three-dimensional plot has the shear stress, τ, as the ordinate and the two stress state variables, $(\sigma - u_a)$ and $(u_a - u_w)$, as abscissas. The surface tangent to the Mohr–Coulomb circles at failure is referred to as the extended Mohr–Coulomb failure envelope for unsaturated soils that defines the shear strength of unsaturated soils. The intersection line between the extended Mohr–Coulomb failure envelope and the frontal plane is the failure envelope for the saturated condition, where the matric suction is zero.

Fig. 2. Photographs of the top soils (a) and granite chips (b).