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Characterization of the constitutive behavior of municipal solid waste considering particle compressibility

Xilin Lü [a,b,*], Xinle Zhai [a], Maosong Huang [a,b]

[a] Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China

[b] Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai 200092, China

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ABSTRACT

This paper presents a characterization of the mechanical behavior of municipal solid waste (MSW) under consolidated drained and undrained triaxial conditions. The constitutive model was established based on a deviatoric hardening plasticity model. A power form function and incremental hyperbolic form function were proposed to describe the shear strength and the hardening role of MSW. The stress ratio that corresponds to the zero dilatancy was not fixed but depended on mean stress, making the Rowe's rule be able to describe the stress-dilatancy of MSW. A pore water pressure reduction coefficient, which attributed to the compressibility of a particle and the solid matrix, was introduced to the effective stress formulation to modify the Terzaghi's principle. The effects of particle compressibility and solid matrix compressibility on the undrained behavior of MSW were analyzed by parametric analysis, and the changing characteristic of stress-path, stress–strain, and pore-water pressure were obtained. The applicability of the proposed model on MSW under drained and undrained conditions was verified by model predictions of three triaxial tests. The comparison between model simulations and experiments indicated that the proposed model can capture the observed different characteristics of MSW response from normal soil, such as nonlinear shear strength, pressure dependent stress dilatancy, and the reduced value of pore water pressure.

1. Introduction

With the development of cities and the rapid growth of urban population, the production of municipal solid waste continually increases, which necessitates extensive construction of landfills. The stability of landfills is very important for the environment and nearby residents. Because landfill failure threatens the properties and lives of residents, this issue has captured the attention of researchers (Seed et al., 1990; Eid et al., 2000; Chang, 2005; Blight, 2008; Giri and Reddy, 2014; Ering and Babu, 2016).

The characterization of the physical and mechanical properties of municipal solid waste is important for the slope stability of landfills. The compressibility and permeability of MSW affects the performance of landfills and can be changed by some influence factors, i.e., components and age (Gabr and Valero, 1995; Karimpour-Fard et al., 2011; Siddiqui et al., 2013; Zekkos et al., 2017). Many factors, including degradation, leachate recirculation and moisture content, affect the mechanical behaviors of MSW and can change the stability of landfills (Gabr and Valero, 1995; Kavazanjian, 2001; Zeccos, 2005; Gabr et al., 2007; Harris et al., 2006; Kavazanjian, 2008; Chen et al., 2009; Machado et al., 2014; Babu et al., 2015). In the experiment process, shredding and test apparatus size also change the physical and mechanical behaviors of MSW, and these factors should be considered in evaluating the engineering properties of MSW (Hossain et al., 2009). The dynamic properties of MSW and landfills were also investigated for the stability of landfills that are subjected to earthquakes (Augello et al., 1995; Kavazanjian, 2000; Zekkos et al., 2014; Ramaiah et al., 2015). Based on these studies, the mechanical behaviors of MSW were obtained; these results are useful for assessing the stability of a landfill and can provide a suitable method for improving safety.

The descriptions of the shear strength and stress-strain relationship of MSW were primarily based on traditional soil mechanics. The Mohr-Coulomb strength criterion was often adopted to describe the shear strength of MSW (Jessberger and Kockel, 1993; Zhu et al., 2003; Zhan et al., 2008; Feng et al., 2017). However, the nonlinear characteristic of shear strength causes the strength parameters to change with the mean stress or confining stress (Vilar and Carvalho, 2002, 2004; Zekkos et al., 2007, Lu et al., 2014). To accurately describe the mechanical behaviors of

* Corresponding author at: Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China.

E-mail address: xilinlu@tongji.edu.cn (X. Lü).

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MSW, some new strength criteria were proposed (Kavazanjian et al., 1995; Stark et al., 2009; Zekkos et al., 2010) and new constitutive models were established based on the experimental results (Machado et al., 2002; Machado et al., 2008; Babu et al., 2010; Feng et al., 2016). Although these proposed criteria and constitutive models were able to describe certain characteristics of MSW, the particle compressibility has not been considered. The compressibility of solid components has a significant effect on the mechanical behaviors of MSW, and Terzaghi's principle of effective stress should be modified when modeling the undrained shear tests results of MSW (Shariatmadari et al., 2009; Karimpour-Fard et al., 2011).

This paper aims to propose a deviatoric hardening plasticity model for MSW, which can consider the shear strength nonlinearity and solid particle compressibility. A power form shear strength criterion was proposed based on fitting existing experimental results. The Rowe's rule was modified by considering the mean stress dependency of stress ratio which corresponds to the zero dilatancy. Terzaghi's principle of effective stress was modified using a rational formula to consider the compressibility of MSW. The ability of the proposed model to predict the drained and undrained behaviors of MSW was demonstrated. The model simulations compare well with the test results obtained by Bhandari and Powrie (2013), Vilar and Carvalho (2004), and Shariatmadari et al. (2014).

2. Shear strength of MSW

The shear strength of MSW is often described by the Mohr-Coulomb criterion as

$$\tau = c + \sigma \tan \varphi \tag{1}$$

where $\tau = (\sigma_1 - \sigma_3)/2$ is the shear strength; $\sigma = (\sigma_1 + \sigma_3)/2$ is the normal stress, and σ_1, σ_3 are the major and minor principal stresses; the strength parameters c and φ are the cohesion and friction angle, respectively; and both parameters can be determined by experiments, i.e., direct shear tests or triaxial tests.

Bray et al. (2009) demonstrated that the shear strength of MSW nonlinearly increases with normal stress; this characteristic cannot be described by the Mohr-Coulomb strength criterion. To calibrate the nonlinear strength, Zekkos et al. (2010) assumed that the cohesion is constant and the friction angle changes with normal stress

$$\tau = c + \sigma \tan\left[\varphi - \Delta\varphi \lg\left(\frac{\sigma}{p_{at}}\right)\right] \tag{2}$$

where $\Delta\varphi$ is a parameter to describe the change of the friction angle with normal stress and P_{at} is the standard atmospheric pressure. When $\Delta\varphi$ is zero, Eq. (2) applies the Mohr-Coulomb strength criterion.

Based on a power form function (Perry, 1994; Baker, 2004), the following strength criterion was adopted

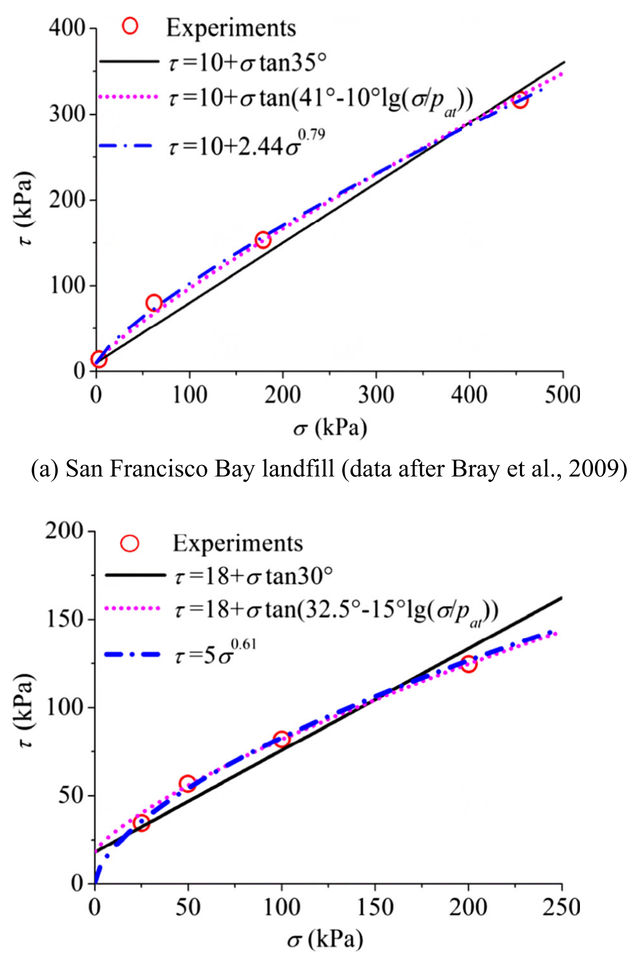
$$\tau = T + B_1 p_{at}\left(\frac{\sigma}{p_{at}}\right)^{\xi} = T + B\sigma^{\xi} = T + \tan(\varphi_e)\sigma^{\xi} \tag{3}$$

where T is the tensional strength; B and B_1 are the strength parameters controlling the slope of the failure envelope; ξ is a non-dimensional parameter that controls the curvature of a failure envelope; p_{at} is the atmospheric pressure; φ_e is the equivalent friction angle obtained from $\tan^{-1}(B)$. When $\xi = 1$, Eq. (3) is equivalent to the Mohr-Coulomb strength criterion, and $T = c$, $B = \tan\varphi$. The introduction of ξ $(0 < \xi \le 1)$ into the failure criterion makes the departure of the shear strength from linearity (Bray et al., 2009; Zekkos et al., 2012) can be captured.

To test the suitability of the nonlinear shear strength criterion, two experimental results of MSW were employed. The first result is the direct shear tests by Bray et al. (2009). The sample was retrieved from a landfill in the San Francisco Bay Area, and all particles of the specimen were smaller than 20 mm. The MSW specimens were 400 × 300 mm rectangles, and the height of the specimens was approximately 150 mm after reconstitution. As shown in Fig. 1(a), the nonlinear strength criterion predicts the nonlinearity of the shear strength of MSW, whereas the Mohr-Coulomb strength criterion cannot achieve a sound prediction. The second experimental result is the direct shear tests by Zhang et al. (2014). The sample was obtained from the Hangzhou Tianziling MSW landfill in China. The diameter and height of the specimens were 180 mm and 150 mm. The shear strength was obtained by the shear stress at 20% shear strain. As shown in Fig. 1(b), the power function fits the experimental data much better than Mohr-Coulomb criterion, and Eq. (3) yields results that are close to Eq. (2).

3. Calculation of the effective stress

Since some solid components in MSW are compressible, the pore-water pressure of MSW subjected to undrained shearing is higher than that of conventional soil (i.e. normally consolidated clay, loose sands) in the case of same shear stress. When the total confining cell pressure is constant, the pore-water pressure can continually increase with an increase in shear stress (Vilar and Carvalho, 2004; Reddy et al., 2009; Karimpour-Fard et al., 2011; Shariatmadari et al., 2014). As shown in Fig. 2, the deformation



(a) San Francisco Bay landfill (data after Bray et al., 2009)

(b) Hangzhou Tianziling landfill (data after Zhang et al., 2014)

Fig. 1. Fitting curve of the MSW shear strength obtained by direct shear tests.

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