Waste Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Constant load and constant volume response of municipal solid waste in simple shear

Dimitrios Zekkos, Xunchang Fei *

Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor 48109-2125, MI, United States

ARTICLE INFO

Article history:
Received 8 February 2016
Revised 5 September 2016
Accepted 21 September 2016
Available online xxxx

Keywords:
Simple shear
Shear strength
Drained
Undrained
Municipal solid waste
Landfills
Stability

ABSTRACT

Constant load and constant volume simple shear testing was conducted on relatively fresh municipal solid waste (MSW) from two landfills in the United States, one in Michigan and a second in Texas, at respective natural moisture content below field capacity. The results were assessed in terms of two failure strain criteria, at 10% and 30% shear strain, and two interpretations of effective friction angle. Overall, friction angle obtained assuming that the failure plane is horizontal and at 10% shear strain resulted in a conservative estimation of shear strength of MSW. Comparisons between constant volume and constant load simple shear testing results indicated significant differences in the shear response of MSW with the shear resistance in constant volume being lower than the shear resistance in constant load. The majority of specimens were nearly uncompacted during specimen preparation to reproduce the state of MSW in bioreactor landfills or in uncontrolled waste dumps. The specimens had identical percentage of <20 mm material but the type of <20 mm material was different. The <20 mm fraction from Texas was finer and of high plasticity. MSW from Texas was overall weaker in both constant load and constant volume conditions compared to Michigan waste. The results of these tests suggest the possibility of significantly lower shear strength of MSW in bioreactor landfills where waste is placed with low compaction effort and constant volume, i.e., "undrained", conditions may occur. Compacted MSW specimens resulted in shear strength parameters that are higher than uncompacted specimens and closer to values reported in the literature. However, the normalized undrained shear strength in simple shear for uncompacted and compacted MSW was still higher than the normalized undrained shear strength reported in the literature for clayey and silty soils.

1. Introduction

Modern municipal solid waste (MSW) landfills are steadily increasing in size to accommodate the growing amounts of generated MSW and to maximize waste containment capacity. Thus, it is becoming more common for many landfills to reach heights of 100 m or more. The slopes of these mega-size facilities need to remain stable under static and dynamic loads. Unfortunately, landfill slope instabilities continue to occur (e.g., Eid et al., 2000; Huvaj-Sarihan and Stark, 2008; Jafari et al., 2013; Zekkos et al., 2014).

Probably the most critical input parameter in assessing the stability of landfill slopes is the shear strength of MSW. A significant number of studies have been conducted to assess the shear strength of MSW in the laboratory using large-size experimental equipment. In this paper, large-size testing is defined as tests that have specimen diameter or width that is at least 300 mm, a definition that is consistent with earlier recommendations (Bray et al., 2009; Athanasopoulos, 2011). Testing of MSW specimens of smaller size is usually not recommended, because bulk waste particles that are influential to the shear strength of waste have to be excluded or shredded to accommodate the size of a specimen (Zekkos et al., 2008; Athanasopoulos, 2011). Most commonly, large-size direct shear testing has been conducted (e.g., Landva and Clark, 1990; Edincliler et al., 1996; Kavazanjian et al., 1999; Mazzucato et al., 1999; Pelkey et al., 2001; Caicedo et al., 2002; Mahler and De Lamare Netto, 2003; Dixon et al., 2008; Bray et al., 2009; Singh et al., 2009; Zekkos et al., 2010a, 2013a; Bareither et al., 2012), but large-size triaxial shear testing has also been conducted (e.g., Jessberger and Kockel, 1993; Grisolia et al., 1995; Bauer et al., 1999; Harris et al., 2006; Zekkos et al., 2012; Ramaiah et al., 2014). A comprehensive literature review and comparison between the reported results of direct shear and triaxial testing of MSW is beyond the scope of this paper and has been done earlier (e.g., Bray et al., 2009, 2011).

* Corresponding author at: 9 EWRE, 1351 Beal Avenue, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, United States.

E-mail address: xcfei@umich.edu (X. Fei).

http://dx.doi.org/10.1016/j.wasman.2016.09.029
0956-053X/© 2016 Elsevier Ltd. All rights reserved.

Simple shear testing has been executed for a large range of natural soils (e.g., Bjerrum and Landva, 1966; Sivathayalan, 1994) and is presently a common test in engineering practice. It can be conducted in both constant load and constant volume conditions which are considered equivalent to "drained" and "undrained" conditions, respectively. However, large-size monotonic simple shear testing of MSW has been conducted as part of four studies only in constant load conditions (Kavazanjian et al., 1999; Pelkey et al., 2001; Yuan et al., 2011; Fei and Zekkos, 2015). Despite the significantly smaller testing record in simple shear of MSW, simple shear testing has important advantages over direct shear and triaxial testing of MSW. MSW has been shown to be one of the most anisotropic ground materials due to the presence of fibrous constituents, such as paper, plastics and wood, which tend to become horizontally oriented during compaction or upon application of a vertical load (overburden). Evidence of this layering has been observed both in the field and the laboratory (Gotteland et al., 2000; Zekkos, 2013). In fact, it has been shown that MSW has many similarities to fibrous peats (Zekkos, 2013). In triaxial testing of MSW, the fibrous waste constituents, i.e., paper, plastic and wood, contribute significantly to the stress-strain response of the MSW specimen. Thus, shear resistances observed in triaxial shear are high, with reported friction angles of 48 degrees or higher (e.g., Zekkos et al., 2012). However, as shown by Bray et al. (2009), in direct shear testing, the horizontal failure plane is parallel to the orientation of the majority of fibrous waste constituents and as a result the shear resistance in direct shear is lower. Still, direct shear testing essentially imposes the failure plane. Given the variability in the constituents of a waste specimen, the imposed horizontal failure plane may not necessarily be the weakest, and a possibly weaker plane may exist that is not tested. Such plane, if present, is more likely to be mobilized in simple shear.

In addition, the overwhelming majority of tests executed to assess the shear strength of MSW have been conducted under "drained" conditions. These testing conditions are appropriate for conventional "dry tomb" landfills where the waste has low moisture content, typically at, or below, field capacity. However, in old or abandoned landfills without a properly operating leachate collection and removal system (LCRS), in conventional "dry tomb" landfills with clogged LCRS, as well as recirculation and bioreactor landfills, the moisture content of the MSW may be significantly higher. The waste may even, in some occasions, become submerged in leachate and, in the absence of gas generation, approach saturation. In addition, there has been field evidence of trapped leachate and gas pressures within layers of waste that are "encapsulated" between daily cover soil layers of lower permeability (e.g., Koerner and Soong, 2000; Jiang et al., 2010; Zhan et al., 2015). In these cases "undrained" conditions may occur and the stress-strain-strength response of MSW in these conditions is important. There are few large-size (>300-mm diameter) tests that have investigated the response of saturated MSW in "undrained" shear and all of them have been obtained from triaxial tests. Bauer et al. (1999) tested mechanically-biologically treated MSW specimens using a 475-mm diameter triaxial device in both drained and undrained conditions. Undrained triaxial shearing has been conducted by Karimpour-Fard et al. (2011) who used a 200-mm diameter triaxial device and Shariatmadari et al. (2009) who tested specimens that were 220-mm in diameter. For both studies the tested waste originated from the Metropolitan Center Landfill in Salvador, Brazil. Tests were also conducted by Harris et al. (2006) and involved 152-mm diameter simple shear testing of MSW and Reddy et al. (2011) that involved tests on synthetic waste specimens that were 50-mm in diameter.

In this study, an experimental dataset of both constant load and constant volume large-size simple shear tests on relatively fresh MSW from two landfills in the United States at their natural moisture content below the field capacity (~30%) is presented with the objective to systematically assess differences in the response of MSW under what are typically considered "drained" and "undrained" shear conditions. The results of this study are particularly important for bioreactor landfills where the unit weight of waste is intentionally low so that liquids can permeate more easily through the waste mass, as well as uncontrolled or old waste dumps without a LCRS or modern landfills with a malfunctioning LCRS.

2. Methodology

2.1. Testing device, materials and procedures

A prototype large-size simple shear device was used in this study. The device, shown in Fig. 1, allows the performance of simple shear tests with a cylindrical specimen that has nominal diameter of 300 mm and a maximum height of 137 mm. The device loading can be stress or displacement controlled. Two micro stepper motors are used to apply the vertical and horizontal loads and two 4.4 kN load cells are used to measure the loads; two displacement transducers are used to measure the vertical and horizontal displacements and calculate the vertical and shear strain of the specimen during shearing. The specimen is prepared within a stack of 6.35 mm thick, Teflon-coated circular aluminum rings that have minimal friction because reinforced membranes of that size are not generally available and are prohibitively expensive to manufacture. An unreinforced specimen membrane is used as a cushion to protect the stacked rings.

MSW from Sauk Trail Hills landfill in Michigan and the Austin Community landfill in Texas was tested. The waste was characterized using the procedures described in Zekkos et al. (2010b). Briefly, these procedures involve the collection of bulk samples of

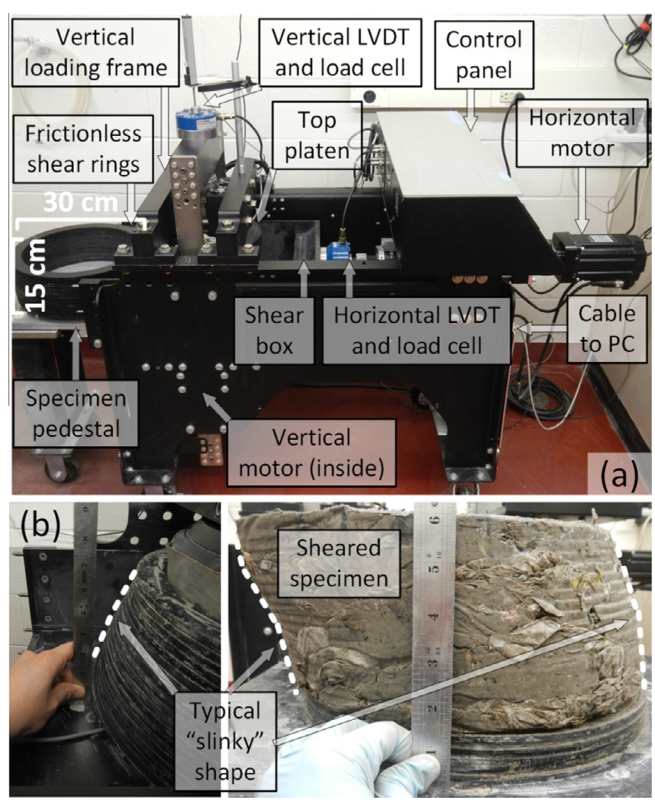

Fig. 1. A view of (a) the simple shear device; and (b) a 300-mm diameter specimen after shear testing.

Please cite this article in press as: Zekkos, D., Fei, X. Constant load and constant volume response of municipal solid waste in simple shear. Waste Management (2016), http://dx.doi.org/10.1016/j.wasman.2016.09.029