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ORIGINAL ARTICLE

Shear strength of municipal solid waste for stability analyses

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Abstract This paper investigates the shear strength of municipal solid waste (MSW) using the back analysis of failed waste slopes as well as field and laboratory test results. Shear strength of MSW is a function of many factors such as waste type, composition, compaction, daily cover, moisture conditions, age, decomposition, overburden pressure, etc. These factors together with non-standardized sampling methods, insufficient sample size to be representative of in situ conditions, and limited shear displacement or axial strain imposed during the laboratory shear testing have created considerable scatter in reported results. Based on the data presented herein, large shear displacements are required to mobilize the peak shear strength of MSW which can lead to displacement incompatibility between MSW and the underlying material(s) such as geosynthetic interfaces and foundation soils. The data presented herein are used to develop displacement compatible shear strength parameters for MSW. Recommendations are presented for modeling the displacement and stress dependent strength envelope in stability analyses.

Keywords Municipal solid waste · Shear strength · Slope stability · Landfill

Introduction

This paper investigates the shear strength of municipal solid waste (MSW). The recommendations presented herein build on previous results and recommendations presented by Eid et al. (2000) and others, such as Gerber (1991), Grisolia et al. (1991, 1995), Jessberger and Kockel (1991), Jessberger (1994), Gabr and Valero (1995), Kockel and Jessberger (1995), Edincliler et al. (1996), Jones et al. (1997), Pelkey (1997), Mazzucato et al. (1999), Thomas et al. (1999), Pelkey et al. (2001), Gabr et al. (2002), Vilar and Carvalho (2004) and Zekkos (2005). Table 1 presents a list of the references and data used herein.

Shear strength testing of MSW is difficult because of the heterogeneous composition of landfill materials, difficulty in sampling, specimen preparation, testing, and range of particle size, and time-dependent properties, such as the age of the MSW and decomposition state, unit weight, etc. Published laboratory and field shear test data and back-analysis of field case histories are used herein to develop a better understanding of MSW shear strength and present recommendations for MSW strength to be used in static and seismic slope stability analyses of landfills.

MSW laboratory test data

Because of the need for a strength envelope in static and seismic slope stability analyses, a basic Mohr–Coulomb approach is utilized herein and by the researchers cited previously to model the shear strength of MSW. The

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Table 1 Summary of MSW shear strength data

References	Testing method and sample size	Sample location	Waste constituents and properties	Displacement or strain at the shearing resistance considered
Landva and Clark (1990)	Laboratory direct shear device (434 × 287 mm)	Edmonton, Calgary, Mississauga, Waterloo in Canada	20–55% Paper products, 5–42% food waste, 4–20% garden waste, 6–15% metal, 2–15% plastic. Dry unit weight = 10–14 kN/m^3	No information
Richardson and Reynolds (1991)	Field direct shear device (150 × 150 mm)	Maine, USA	Dry unit weight = 16 kN/m^3 (Gerber 1991)	No information
Houston et al. (1995)	Field direct shear device (1.2 × 1.2 m)	Northwest Regional Landfill in Arizona	MSW, construction, and landscaping waste	Shear displacement of 2.5 cm
Withiam et al. (1995)	Field direct shear device (150 × 150 cm)	Dekorte Park Landfill in New Jersey	Glass, paper, cinders, plastic, metal and building debris. Dry unit weight = 10.8–12.8 kN/m^3	No information
Edincliler et al. (1996)	Laboratory direct shear device (30 cm diameter)	Southeastern Wisconsin Landfill	Fresh waste. Dry unit weight = 7.5–14.2 kN/m^3	Shear displacement of 2.5 cm
Siegel et al. (1990)	Laboratory direct shear device (13 cm diameter)	California Landfill	10–48-Year old waste. Dry unit weight = 9.6–17.3 kN/m^3	Shear displacement of 1.3 cm
Del Greco and Oggeri (1994) from Oweis and Khera (1998)	Laboratory direct shear device	No information	Baled MSW. Dry unit weight = 5–7 kN/m^3	No information
Kockel and Jessberger (1995); Jessberger and Kockel (1993)	Laboratory drained triaxial compression device (60 cm long × 30 cm diameter specimen)	Germany Landfill	1– 3-Year-old waste	10% Axial strain
Taylor (1995) from Van Impe (1998)	Laboratory simple shear device (no size)	No information	38% Paper, 18% plastics, 17% textiles; 3-month-old waste	10% Shear strain
Gabr and Valero (1995) from Van Impe (1998)	Laboratory direct shear device (6.4 cm diameter)	Pennsylvania Landfill	33% Ash, soil and rock, 23% textiles, 13% plastics, 10% metals, etc; 15–30 years old. Dry unit weight = 10–12.1 kN/m^3	Shear displacement of 6 mm
Kavazanjian et al. (1999)	Laboratory direct shear device (46 cm diameter)	California Landfill	11–35-Year-old	1.9% Shear strain
Mazzucato et al. (1999)	Field cylindrical direct shear device (80 cm diameter)	Italy Landfill	Total unit weight = 7 kN/m^3	Shear displacement of 2.5 cm
Thomas et al. (1999)	Field direct shear device (1 m × 1 m)	Torcy, France	20% Plastics, 21% paper, 11% textile. Total unit weight = 7.8–16 kN/m^3	Shear displacement of 2.5 cm
Pelkey et al. (2001); Pelkey (1997)	Laboratory direct shear and direct simple shear device (45 cm long × 30.5 cm wide)	Three Landfills in Canada	Shredded and un-shredded MSW; 2–5-year-old waste. Total unit weight 10–16 kN/m^3	Shear displacement 2.5 cm or 10% shear strain

Table 1 continued

References	Testing method and sample size	Sample location	Waste constituents and properties	Displacement or strain at the shearing resistance considered
Gabr et al. (2002)	Laboratory direct shear device (10 cm square)	Synthetically generated waste	No information	Maximum shear displacement of 1.2 cm
Machado et al. (2002)	Laboratory consolidated-drained triaxial compression device (30 and 40 cm long × 15 and 20 cm diameter specimen)	Sao Paulo, Brazil	55% Soil and organic paste, 17% plastics, 10% stone etc. 15 years old waste. Total unit weight = 10 kN/m^3	10% axial strain
Vilar and Carvalho (2004)	Laboratory consolidated-drained triaxial compression device (30 and 40 cm long × 15 and 20 cm diameter specimen)	Sao Paulo, Brazil	55% Soil and organic paste, 17% plastics, 10% stone, etc.; 15 years old waste. Total unit weight = 10–12 kN/m^3	10% Axial strain
Gomes et al. (2005)	Laboratory consolidated-drained triaxial compression device	Portugal	37% Plastics, 33% textile, 11% soil, and 10% metal. Total unit weight 11.5 kN/m^3	10% Axial strain
Itoh et al. (2005)	Laboratory consolidated-drained triaxial compression device (23 cm × 24 cm × 57.5 cm high specimen)	Tokyo Landfill	Maximum dry density 0.6–0.7 g/cm^3	10% Axial strain
Harris et al. (2006)	Laboratory direct simple shear device (15 cm diameter, 5 cm height)	Mohawk landfill, NY and Outer Loop landfill, KY	Shredded and processed MSW. 2–10-year-old waste. Total unit weight 11–17.5 kN/m^3	10% Shear strain
Isenberg (2003)	Laboratory direct simple shear device (15 cm × 15 cm × 5 cm)	Hiriya landfill, Israel	Decomposed waste. Unit weight 16 kN/m^3	No information
Grisolia et al. (1991) from Jessberger and Kockel (1993)	Laboratory triaxial device	No information	No information	10% Axial strain
Caicedo et al. (2002)	Field direct shear device (90 cm diameter)	Dona Juana landfill, Colombia	48% Organic matter, 45% paper, textile, and plastics, 7% soils, metals, and glass. Fresh MSW. Total unit weight 10 kN/m^3	No information

summary of shear strength data presented herein should be regarded as a generalization necessitated by the need for a strength envelope and should be used with considerable engineering judgment. There is an increasing need for estimating the shear strength of MSW because of an emphasis on stability analyses after a number of landfill slope failures. This need is greatest because the height of proposed landfills is increasing. The increasing height of landfills is to increase disposal capacity and can involve a new facility or a vertical expansion of an existing facility. This trend now includes proposed facilities that exceed an MSW depth of 180 m.

There is a wide range of effective stress shear strength parameters for MSW reported in the literature. Effective stress parameters are used in both static and seismic stability analyses because the high permeability of MSW usually does not allow generation of significant shear induced pore-pressures prior to or during slope instability unless aggressive leachate recirculation is being conducted. In general, if the MSW has a moisture content less than the field capacity of the MSW, shear induced pore pressure probably will not develop. Thus, effective stress stability analyses are usually performed to evaluate the stability of landfills.

Reported values of MSW effective stress friction angle (ϕ') range from 10 to 53° while effective stress cohesion (c') ranges from 0 to 67 kPa. This range is caused by the numerous factors that influence the test results including the inherent heterogeneous nature of waste, sample age, degree of decomposition, composition of the waste, specimen size, unit weight, pre-test processing, test method, and test conditions (Edincliler et al. 1996; Manassero et al. 1996; Van Impe 1998; Isenberg 2003). Large-scale laboratory direct shear tests (at least 30 cm × 30 cm dimensions) on MSW samples obtained from field borings, or excavations, and in situ direct shear tests (as large as 1 m × 1 m) on as-compacted MSW are common methods used to determine the shear strength of MSW (see Table 1). Of course, the representative nature of these samples is debatable but the testing provides some guidance on the shear strength of MSW. These limitations suggest that back-analysis of failed waste slopes should be used to guide the laboratory strength parameters.

Shear behavior of MSW

Effect of shear displacement/axial strain

The shear strength of MSW is shear displacement or axial strain dependent and tends to increase with increasing deformation (Eid et al. 2000). Review of existing laboratory data shows that most of the laboratory shear tests investigated are not continued to a sufficient displacement or strain to mobilize the peak strength of the MSW. Instead the shear test is terminated prior to mobilization of the peak shear resistance (Gerber 1991; Grisolia et al. 1991; Jessberger and Kockel 1991; Jessberger 1994; Gabr and Valero 1995; Kockel and Jessberger 1995; Edincliler et al. 1996; Jones et al. 1997; Mazzucato et al. 1999; Thomas et al. 1999; Bouzza and Wojnarowicz 2000; Pelkey et al. 2001; Gabr et al. 2002; Vilar and Carvalho 2004).

Figure 1 shows typical shear stress–displacement relationships from direct shear tests on MSW. The shear boxes used in these studies range from 15 to 100 cm long, 15 to 100 cm wide, and 22 to 30 cm deep. The tests were terminated at various shear displacements with the maximum shear displacement being about 250 mm. In most of the tests, the measured shear stress is still increasing when the direct shear test was terminated. From Fig. 1 a shearing displacement substantially greater than 150 mm is usually required to achieve the peak shear resistance of MSW. Pelkey et al. (2001) show the shear strength of MSW at different shear displacement levels and conclude that the peak shear strength of MSW is reached at a shear displacement of 100–220 mm (in a direct shear box that is 450 mm long and 305 mm wide with upper and lower shear boxes each 300 mm deep).

Stark et al. (2000) conclude that the shear strength of MSW increases with increasing strain or displacement. This leads to high strength values that are in good agreement with field observations of vertical scarps from landfill slope failures remaining near vertical for significant periods of time. Stark et al. (2000) conclude that the MSW acts

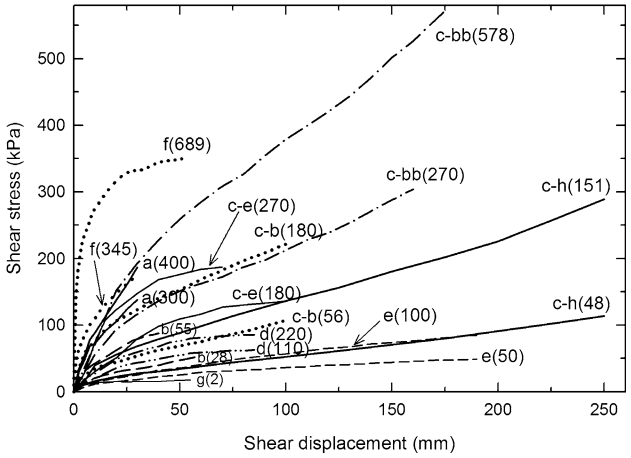

Fig. 1 Stress–displacement relationships from direct shear tests on MSW. *Letters* indicate different references and numbers in parenthesis are the testing normal stresses in kPa. [*a* Taylor 1995, *b* Edincliler et al. 1996, *c* Pelkey 1997 (*c*, *b* Blackfoot refuse, *c*, *bb* Blackfoot/Burbank refuse, *c*–*e* Edmonton shredded refuse, *c*–*h* Hantsport old refuse], *d* Mazzucato et al. 1999, *e* Thomas et al. 1999, *f* Harris et al. 2006, *g* Zekkos 2005)

as a reinforced mass and additional strain/displacement mobilizes the reinforcing effect of plastics, rope, fabrics, and other materials.

Figure 2 presents strength envelopes for MSW obtained from the direct shear data from the references summarized in Fig. 1 for various shear displacements. The data symbols used in Fig. 2 correspond to different levels of shear displacement. The lowest strength envelope corresponds to a shear displacement of 10 mm and the highest strength envelope corresponds to a shear displacement of 150 mm. This reaffirms increasing shear resistance with increasing shear displacement in direct shear tests, and shows the shear resistance can increase by a factor of two depending on the applied shear displacement.

Figure 2 also presents equations for the various strength envelopes that can be used to estimate the shear resistance of MSW for a given level of shear displacement. For example, if an estimated permanent seismic deformation of 100 mm is being considered, the shear resistance of MSW can be estimated using the strength envelope that corresponds to 100 mm of shear displacement in Fig. 2.

Figure 3 shows typical deviator stress (σ_1–σ_3) versus axial strain relationships from isotropically consolidated-drained triaxial compression tests on MSW. The triaxial compression specimens range from 15 to 30 cm in diameter and 30 to 60 cm long. The tests were conducted to a maximum axial strain of 46% which corresponds to a vertical displacement of 21 cm based on an initial specimen height of 45 cm. As can be seen in Fig. 3, triaxial compression data on MSW consistently shows the deviator stress increasing continuously with axial strain, without reaching a well-defined peak value (Singh and Murphy 1990; Machado et al. 2002; Vilar and Carvalho 2004). This is in contrast to the direct shear data, which sometimes reaches a peak or ultimate value (see Fig. 1) prior to test termination. It is anticipated that this difference is caused by the difference in the mode of shear and magnitude of displacement applied in the direct shear and triaxial devices.

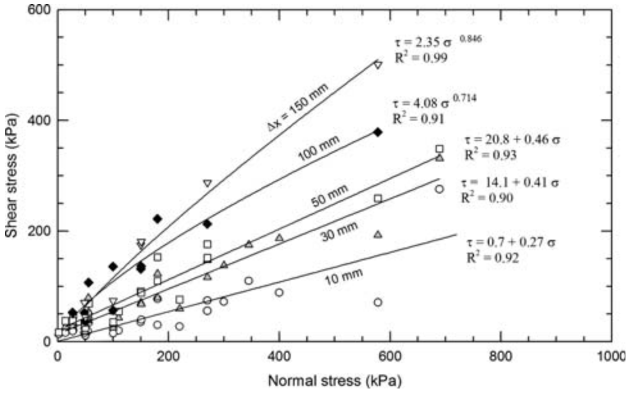

Fig. 2 Strength envelopes for MSW corresponding to 10, 30, 50, 100 and 150 mm of shear displacement (Δx) in direct shear tests

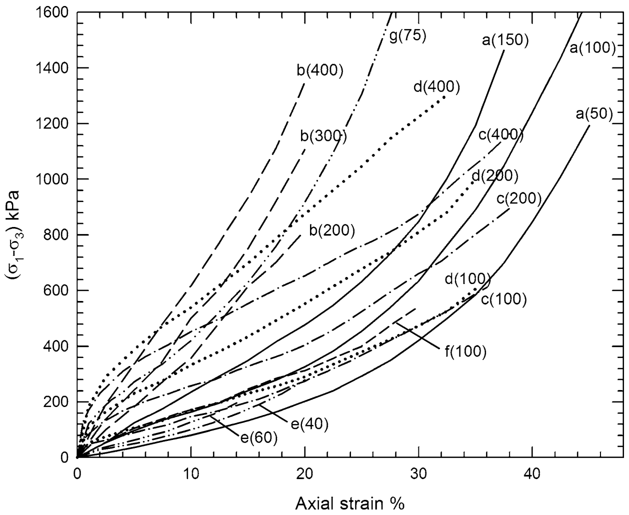

Fig. 3 Stress–strain relationships of MSW from triaxial compression tests. *Letters* indicate different references, and *numbers* in *parenthesis* are the consolidation pressures in kPa. (*a* Grisolia et al. 1991, *b* Jessberger and Kockel 1993, *c* Machado et al. 2002, *d* Vilar and Carvalho 2004, *e* Itoh et al. 2005, *f* Gomes et al. 2005, *g* Zekkos 2005)

Figure 4 presents strength envelopes from isotropically consolidated triaxial compression tests on MSW obtained from the studies summarized in Fig. 3 for various levels of axial strain. The lowest strength envelope corresponds to

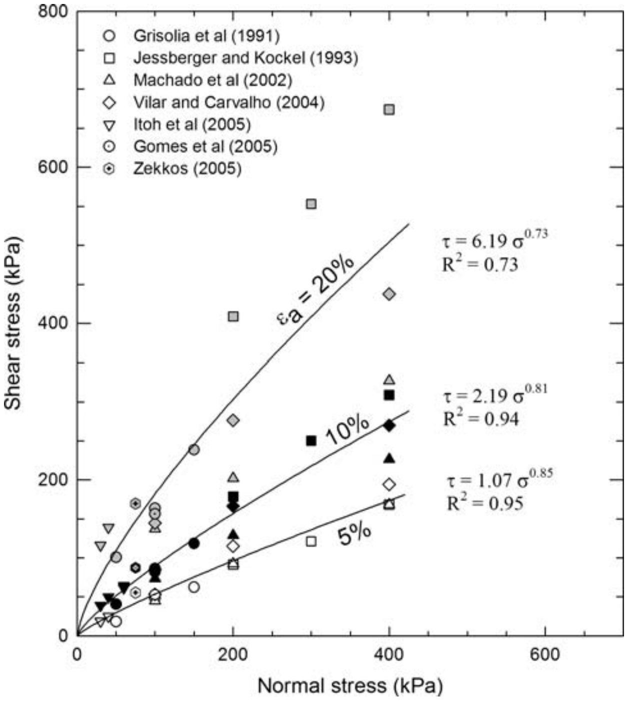

Fig. 4 Strength envelopes of MSW, corresponding to 5, 10 and 20% axial strain in triaxial compression tests. *White symbols* are for 5% axial strain, *black symbols* for 10% and *gray symbols* for 20%

an axial strain of 5% and the highest strength envelope corresponds to an axial strain of 20%. This also affirms increasing shear resistance with increasing axial strain in triaxial compression tests on MSW. Figure 4 also presents equations for the various strength envelopes that can be used to estimate the shear resistance of MSW for a given level of axial strain.

Grisolia et al. (1995) performed triaxial compression tests on MSW and report that even at axial strains in excess of 20–30%, the peak shear strength is not mobilized. They present their findings in the form of mobilized friction angle and cohesion as a function of axial strain. At an axial strain of 10%, the mobilized cohesion of 5 kPa and a friction angle of 10° are reported while a cohesion of 30 kPa and a friction angle of 20° is reported for an axial strain of 25%. Vilar and Carvalho (2004) described drained isotropically consolidated triaxial compression tests on 200 mm in diameter and 400 mm high specimens and report stress–strain relationships that are concave upwards. Thus, the peak strength is not achieved even at axial strains up to 30%. They also recommend that the resulting shear strength envelopes be based on the axial strain at which the particular deviator stress is obtained. Their triaxial data suggest that the frictional resistance of the MSW tends to be fully mobilized at axial strains of less than or equal to 20% while the cohesion intercept starts to be mobilized at axial strains of 10% or more. A limiting value of strain for mobilization of the cohesion intercept could not be discerned from the data (Vilar and Carvalho 2004). This may be beneficial for seismic analyses that predict a large amount of earthquake-induced permanent deformation because the cohesion intercept significantly influences the calculated factor of safety (FS) and yield acceleration (Stark and Choi 2004).

The shear displacement or axial strain dependency of MSW shear strength has created some confusion in the literature because the reported strength parameters correspond to different displacements or different axial strains. The reported MSW strength parameters usually correspond to the measured shear stress at the displacement or axial strain at test termination because the shear resistance is frequently still increasing. This is problematic because the range of displacement or axial strain that can be applied in shear devices varies considerably. This incompatibility probably results in some of the observed variability in the reported strength parameters. It is recommended that laboratories include a subscript to their strength parameters that indicates the displacement or axial strain at which the MSW strength parameters are determined. Others recognized the problem of reporting strength parameters for MSW when the failure point is not clearly defined or reached before the test is terminated. For example, Vilar and Carvalho (2004) and Harris et al. (2006) recommend that the Mohr–Coulomb criterion be related to some value of axial strain.

Isenberg (2003) emphasizes that waste shear strength and density are a function of site specific waste composition and operational techniques, such as waste type, composition, compaction, daily cover, moisture conditions, age, overburden pressure, etc. Isenberg (2003) reports peak shear strength parameters that range from $\phi' = 20–35°$ and $c' = 0–50$ kPa. These shear strength parameters are in agreement with the values proposed by Eid et al. (2000) of $\phi' = 35°$ and $c' = 0–25$ kPa. Milanov et al. (1997) report the most likely or reasonable shear strength parameters of MSW are c'= 1–2 kPa and $\phi' = 35–40°$.

Therefore, it is suggested that MSW shear strength parameters be reported with the displacement or axial strain level at test termination or where the shear strength parameters are being determined as will be presented herein.

Effect of normal stress

Increasing demand for vertically expanding existing landfills and the interest in mega-landfills, has created a need for characterizing the shear strength of MSW at high normal stresses. Therefore, the stress dependency of MSW shear strength parameters is discussed in this section. Figures 2 and 4 demonstrate the dependence of MSW shear strength on the magnitude of normal stress as well as shear displacement or axial strain.

The data and shear strength envelopes presented in Fig. 4 show clearly the stress-dependent nature of the Mohr–Coulomb strength envelope of MSW. The nonlinearity of the strength envelope can be evaluated in terms of the mobilized secant friction angle (as defined by Stark and Eid 1994), the value of which is decreasing with increasing normal stress. This indicates the importance of the stress-dependent nature of the MSW shear strength. Del Greco and Oggeri (1994) also suggested that the shear strength of MSW is stress dependent for normal stresses up to 110 kPa and recommended a stress dependent friction angle as early as 1994. There is little data at normal stresses greater than 500 kPa. A normal stress of 500 kPa corresponds to a waste depth of only 40 m based on a typical waste unit weight of 12.6 kN/m^3 (80 pcf). A waste depth of 40 m is considerably smaller than depths of 180 m, which are currently being proposed. Thus, it is prudent to be conservative at normal stresses greater than 500 kPa.

Figure 5 presents all of the laboratory data compiled during this study and described in Table 1. One important aspect of this data is the normal stress range up to 1,800 kPa, which corresponds to a waste height of about 145 m based on a typical waste unit weight of 12.6 kN/m^3. This height approaches the height currently being proposed for a landfill with a height of 180 m. Prior MSW strength relationships do not extend beyond 400 kPa and thus have

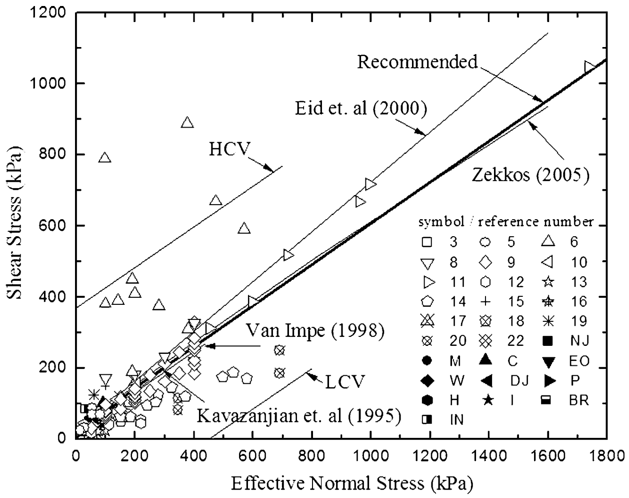

Fig. 5 Summary of measured and back-calculated MSW shear strength for effective normal stresses less than 1,800 kPa

limited applicability for mega-landfills and significant vertical expansions because MSW shear strength is normal stress dependent.

As expected, the data in Fig. 5 show considerable scatter but a trend of nonlinear increase in shear resistance with increasing normal stress is evident for normal stresses less than 1,000 kPa. Two bracketing trend lines are presented in Fig. 5 to facilitate the use of this data in evaluating the reliability of landfill slopes, which is discussed subsequently.

Reliability of landfill slopes

The probability of failure and reliability of the computed factor of safety (FS) of landfill slopes can be estimated using the method described by Duncan (2000). This procedure requires estimating the standard deviation in the quantities impacting the computed FS; one of which is MSW shear strength. Thus, the standard deviation of the MSW strength must be estimated to calculate the change in the FS due to the standard deviation in MSW strength. A Taylor series is used to estimate the standard deviation and variance in the FS based on the change in FS caused by the standard deviation in all of the parameters that influence the FS (Duncan 2000). The standard deviation in the factor of safety (σ_F) is estimated using the following Taylor series expression:

$$\sigma_F = \sqrt{\left(\frac{\Delta F_1}{2}\right)^2 + \left(\frac{\Delta F_2}{2}\right)^2 + \left(\frac{\Delta F_3}{2}\right)^2}$$

where ΔF is the change in factor of safety computed for the most likely value (MLV) +1 SD and the MLV −1 SD for the parameter in question. Thus, the change in factor of safety for the MSW strength envelope in Fig. 5 that correspond to the most likely strength envelope +1 and the most likely strength envelope −1 SD must be estimated.

The two trend lines in Fig. 5 can be used to estimate the highest (HCV) and lowest conceivable values (LCV) of the strength envelope for calculation of the SD of the MSW strength. The three-sigma rule is used to estimate the SD of a parameter because 99.7% of all values of a normally distributed parameter fall within three SDs of the value (Dai and Wang 1992). This assumes that the HCV and LCV correspond to values that are three SDs above and below, respectively, the average value (Duncan 2000). Figure 5 shows that the HCV and LCV strength envelopes encompass about 98% of the data shown for normal stresses less than 600 kPa and thus the trend lines are reasonable approximations of the HCV and LCV. Using the HCV and LCV in Fig. 5, the SD of strength can be calculated using the following expression:

$$\sigma = \frac{(\mathrm{HCV} - \mathrm{LCV})}{6}$$

The data presented herein can be used to estimate the reliability of landfill slopes instead of simply reporting a value of FS.

Recommended MSW shear strength parameters

Shear strength parameters at normal stresses less than 200 kPa

Figures 5 and 6 present all of the laboratory data compiled during this study and described in Table 1 for normal stresses less than 1,800 and 500 kPa, respectively,

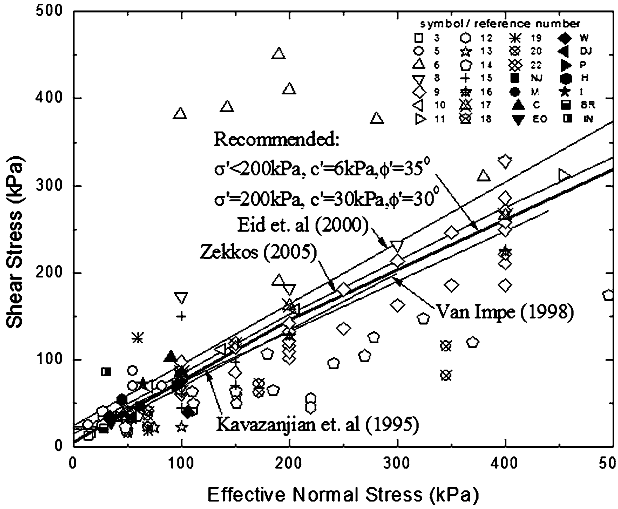

Fig. 6 Recommended strength envelope for effective normal stresses less than 500 kPa

which correspond to a shear displacement less than or equal to 25 mm or an axial or shear strain less than or equal to 10%. A shear displacement of 25 mm and an axial strain of 10% are used because these values are compatible with the stress–strain behavior of geosynthetic interface and foundation soil (Eid et al. 2000). Compatible shear displacement–shear stress relationships are illustrated in Fig. 6 of Eid et al. (2000), showing that the cohesive soil and MSW mobilize a peak strength at a shear displacement less than 2.5 mm and greater than 40 mm, respectively. Back-analysis of field case histories show that the mobilized resistance of MSW corresponds to the shear resistance at a displacement of about 25 mm. Eid et al. (2000) recommended MSW shear strength parameters of $c' = 25$ kPa and $\phi' = 35^\circ$ which corresponds to a shear resistance of about 64 kPa for a normal stress of 55 kPa. Figure 6 of Eid et al. (2000) shows that a shear resistance of 64 kPa is mobilized in the direct shear test on MSW at a shear displacement of 20–25 mm. Because MSW exhibits a much higher peak strength and direct shear testing is usually conducted to at least 25 mm of shear displacement, a 25 mm is used to define the strength of MSW. A corresponding value of axial strain is about 10%.

Zekkos et al. (2007) recommends failure criterion based upon $K_o = 0.3$ and an additional 5% of axial strain in triaxial compression tests. The data presented by Zekkos et al. (2007) show a better regression coefficient when a failure criterion of $K_o = 0.3$ and an additional 10% of axial strain is used, which is in better agreement with Eid et al. (2000) and the axial strain of 10% recommended herein. Using an axial strain of 5% appears to be conservative for MSW based on vertical slopes in MSW that remain stable for long period of time.

Zekkos et al. (2007) use the variable K_o to define different points on the stress–strain relationship. The use of K_o is confusing because K_o is usually used to represent the coefficient of lateral earth pressure at rest, not a point after shearing has commenced in a triaxial compression test. The variable K is more representative and is the ratio of the major (σ_1) and minor (σ_3) principal stresses. In various ICD triaxial compression tests conducted by Zekkos (2005) the ratio of σ_1 to σ_3 of 0.3 occurred at an axial strain of 2–9%. Thus, the failure criterion of $K = 0.3$ and an additional axial strain of 5% corresponds to an axial strain of about 7–14%. The failure criterion of $K = 0.3$ and an additional axial strain of 10%, which exhibits a higher regression coefficient, corresponds to an axial strain of about 12–19%. The average of these criteria is an axial strain of 10% as recommended by Eid et al. (2000) and herein. A failure criterion of 10% axial strain in ICD triaxial compression tests is also less confusing. The amount of axial strain that occurs at a particular ratio of σ_1 to σ_3 is a function of confining pressure, waste composition, specimen preparation and compaction, and strain rate.

In summary, stress–strain compatible failure criteria for MSW appears to be a shear displacement of 25 mm or an axial strain of 10% in ICD triaxial compression tests.

Superimposed on data in Figs. 5 and 6 are several strength envelopes recommended by Kavazanjian et al. (1995), Van Impe (1998), Zekkos (2005) and Eid et al. (2000). Kavazanjian et al. (1995) suggest the following shear strength parameters for MSW: $c' = 24$ kPa and $\phi' = 0^\circ$ for normal stress range of 0–30 kPa, $c' = 0$ and $\phi' = 33^\circ$ for normal stress range of 30–300 kPa. Van Impe (1998) summarizes the shear strength of MSW data from laboratory tests as well as from back-analysis of case histories, suggesting a strength envelope defined by $c' = 20$ kPa and $\phi' = 0^\circ$ for an effective normal stress range of 0–20 kPa. For the 20–60 kPa normal stress range, he recommends $c' = 0$ and $\phi' = 38^\circ$ and for normal stresses greater than 60 kPa $c \geq 20$ kPa and $\phi' = 30^\circ$. Thus, Van Impe (1998) recommends a tri-linear envelope to capture the stress dependent nature of MSW. Zekkos (2005) also recommends a stress-dependent strength envelope where friction angle decreases with confining stress.

Also shown in Figs. 5 and 6 is the linear strength envelope proposed by Eid et al. (2000) in terms of $c' = 25$ kPa and $\phi' = 35^\circ$. Eid et al. (2000) selected a linear envelope because the data considered in their study is limited to normal stresses less than 350 kPa. This strength envelope plots above the strength envelopes of Van Impe (1998) and Kavazanjian et al. (1995). The Eid et al. (2000) envelope was chosen so that it plots above the lowest MSW shear strengths measured in laboratory tests because the mobilized strength, i.e., the presence of stable vertical or near vertical landfill slopes after a slope failure and back-analysis of landfill slope failures, is greater than the strength parameters of $c' = 25$ kPa and $\phi' = 35^\circ$. Thus, the Eid et al. (2000) envelope is a lower bound on field data of MSW shear strength. Eid et al. (2000) concluded it would be too conservative to capture the lowest laboratory measured strengths at normal stresses less than 200 kPa because of limitations in MSW specimen preparation, testing equipment, and magnitude of applied shear displacement.

The authors do not believe that the recommended or MLV strength envelope should plot below all of the laboratory measured shear strengths at normal stresses less than 200 kPa as suggested by Kavazanjian et al. (1995). However, the recommended strength envelope should plot at or near the lower bound of the field or back-calculated shear strength values. Kavazanjian et al. (1995) base their strength envelope on the lower bound of the laboratory and back-calculated data, as they should because they use back-calculation of non-failed slopes to reinforce the laboratory data. The problem with back-calculating non-failed slopes is the FS is not known. In contrast, Eid et al. (2000) only back-calculated failed slopes in which sufficient information is available to perform a meaningful back-analysis. It will be shown subsequently a different rationale is used to develop a strength envelope for normal stresses greater than or equal to 200 kPa because of a lack of field case histories at these normal stresses.

Finally, it is recommended that the reliability of the computed FS be estimated using the methodology presented by Duncan (2000) so the recommended strength envelope in this study should be used as the MLV for normal stress less than 200 kPa.

Importance of MSW strength parameters at normal stresses less than 30 kPa

Kavazanjian et al. (1995) and Van Impe (1998) recommend different strength parameters for normal stresses less than 30 kPa. In a stability analysis a normal stress of 30 kPa on an inclined failure surface through the waste mass corresponds to a waste depth of about 4.8 m assuming a coefficient of lateral earth pressure of 0.5. An inclined failure surface through the waste is used because landfill slope failure usually involves a transitional slide along a weak underlying layer (Stark et al. 2000). If a coefficient of lateral earth pressure of 0.3 is used as recommended by Zekkos (2005), 30 kPa corresponds to a waste depth of 8 m. The lateral earth pressure coefficient is used because the stress normal to the inclined failure surface is desired. The depth of 4.8 m is calculated by dividing the normal stress of 30 kPa by a typical MSW unit weight (12.6 kN/m^3), and the lateral earth pressure coefficient.

Most landfills are much deeper than 4.8 m, especially mega-landfills, so the initial horizontal portion of the strength envelope only impacts an extremely small portion of the critical failure surface that passes through the MSW. A sensitivity analysis shows that varying the strength parameters in the upper 4.8 m of the critical failure surface that extends to the liner system in a deep landfill does not significantly impact the calculated FS for waste depths greater than about 15 m as compared to the strength parameters recommended by Eid et al. (2000). Thus, the refinement of the MSW failure at normal stresses less than 30 kPa does not appear to be warranted for landfills with a waste depth greater than about 15 m. However, refinement of the strength envelope at normal stresses greater than 300 kPa is important because the MSW shear strength parameters are known to be confining stress dependent.

Shear strength parameters at normal stresses greater than 200 kPa

The MSW strength data for normal stresses greater than about 200 kPa used by Eid et al. (2000) shows a nonlinear increase in shear strength with increasing normal stress as pointed out by discussers (see Stark et al. 2001). Thus, this paper provides recommendations for strength parameters for normal stresses greater than 200 kPa to overcome this limitation of the recommendation in Eid et al. (2000). Although some of the data in the higher normal stress range suggest that the strength envelope is linear (e.g. Kavazanjian et al. 1995), most of this data has a waste percentage of less than 30% (soil percentage of about 60–70%), which means that the materials tested probably should not be classified as waste. Recent data by Pelkey (1997), Pelkey et al. (2001) and Van Impe (1998) suggest that the slope of the shear strength envelope decreases as the normal stress increases.

Figures 5 and 6 represents the bi-linear strength envelope that captures the stress dependency of MSW at effective normal stresses greater than 200 kPa. For normal stresses less than 200 kPa, $c' = 6$ kPa and $\phi' = 35^\circ$ is recommended which is consistent with Eid et al. (2000) but utilizes a c' of six instead of 25 kPa. Even with the reduced c' value, the recommended strength envelope exceeds the strength envelopes proposed by Kavazanjian et al. (1995) and Van Impe (1998) for the applicable normal stresses.

For normal stresses greater than or equal to 200 kPa, the recommended strength envelope changes to $c' = 30$ kPa and $\phi' = 30^\circ$ to represent the stress dependency of MSW shear strength. A normal stress of 200 kPa on an inclined failure surface through the waste corresponds to a waste depth about 32 m assuming a coefficient of lateral earth pressure of 0.5 and a typical waste unit weight of 12.6 kN/m^3. If the landfill has a waste depth of less than 32 m, the strength parameters of $c' = 6$ kPa and $\phi' = 35^\circ$ can be used. If the landfill depth is greater than or equal to 32 m, the bilinear envelope should be used. To facilitate the use of the bi-linear envelope in stability analyses, the bilinear envelope can be approximated using the following expression:

$$\tau = 15 + 0.61\sigma'_n - 0.00002\left(\sigma'_n\right)^2$$

Alternatively, various points on this bilinear envelope, i.e. various pairs of shear and normal stress values, can be used in slope stability softwares to model the strength envelope directly.

Recommended strength envelope in this study is consistent with the recent recommendation by Zekkos (2005) reporting the strength envelope of MSW as:

$$\tau = c + \sigma'_n \cdot \tan \phi'$$

where $c = 15$ kPa. Considering the decrease in friction angle with increasing confining stress, Zekkos (2005) recommended the following equation for the shear strength of MSW, where P_o is 1 atm.:

$$\tau = 15 + \sigma'_n \cdot \tan\left[36 - 5 \cdot \log\left(\frac{\sigma'_n}{P_o}\right)\right]$$

Figure 5 shows good agreement between the recommended bilinear envelope and the envelope corresponding to the equation above. A bilinear strength envelope to model MSW is also suggested by Del Greco and Oggeri (1994), Pelkey et al. (2001), and Gabr et al. (2002).

The recommended strength parameters or equation developed herein above results in a strength envelope that plots below the Eid et al. (2000) strength envelope as shown in Fig. 5. This is because the recommended strength envelope plots at or near the lower bound of the new case histories analyzed herein, which provide the best estimate of mobilized MSW strength. These case histories are discussed subsequently.

Figure 5 also shows that the recommended strength envelope at normal stresses greater than 200 kPa plots at the lower bound of the laboratory measured shear strength values because there is a lack of field case histories that correspond to normal stresses significantly greater than 200 kPa. Thus, it is prudent to use a strength envelope near the lower bound of the laboratory measured shear strength values because field case histories are not available to confirm the laboratory measured shear strength values. As a result, the recommended strength envelope captures the one data point at a normal stress of about 1,750 kPa. Clearly, additional data is needed at higher normal stresses to confirm this recommended strength envelope.

The bilinear strength envelope shown in Fig. 5 still depicts MSW as a strong material. The high strength of MSW is confirmed by landfill slopes that can stand at steep angles for considerable time (Koelsch 1993). Examples of steep landfill slopes are reported by various researchers, e.g. 60-m-high nearly vertical scarp that resulted from the slope failure of a Cincinnati landfill which remained stable for 10 months until it was remediated (Stark et al. 2001), 21-m-high vertical excavation in MSW in Illinois which has remained stable over 10 years (Stark et al. 2001), 1H:3 V (about 71°) slope in the Umraniye dump site in Istanbul (Kocasoy and Curi 1995), a 75° slope excavated in Goettingen–Deiderode landfill in Germany (Koelsch 2005), stable 1.2H:1 V and 0.67H:1 V slopes in Hiriya landfill in Israel five years after a slope failure in 1997 (Isenberg 2003), and a vertical scarp after the Payatas landfill slope failure in Philippines in 2000 (Merry et al. 2005). Based on the observation of steep landfill slopes that remain stable, it is concluded that the focus of landfill stability analyses should be the materials that underlie the MSW, e.g., geosynthetic interfaces and weak foundation soils, and not the MSW unless there is a weak continuous layer in the waste mass.

Back-calculated MSW shear strength from failed waste slopes

Kavazanjian et al. (1995) back-analyzed unfailed landfill slopes to estimate the shear strength of MSW. The landfill slopes (Lopez Canyon, CA; OII Landfill, CA; Babylon, New York; Private Landfill, OH) had not failed or experienced movement, therefore they assumed a FS equal to 1.2 for the slope. Using a FS equal to 1.2 and assuming a c' of 5 kPa, they back-calculated the MSW friction angle. More recent data suggests a greater cohesion than 5 kPa which will reduce the back-calculated value of ϕ'.

Eid et al. (2000) analyzed four landfill slope failures to estimate the mobilized strength of MSW. Other case histories were considered for back-analyses but not included in that study because of significant uncertainties in some of the field conditions, such as slope geometry, leachate level, and subsurface information. These four case histories are included in Figs. 5 and 6 and reinforce the recommended bi-linear strength envelope.

Seven additional landfill slope failures were analyzed and Table 2 summarizes all of the case histories analyzed to date. The back-analyses of Warsaw, Poland; Istanbul, Turkey; Payatas, Philippines and Hiriya, Israel landfills are discussed in Huvaj-Sarihan and Stark (2008). Cruz das Almas-Brazil and Leuwigajah-Indonesia landfill slope failures were analyzed as part of this study.

One of these slope failures involves the Gnojna Grora Hill landfill, in Warsaw, Poland (Bouzza and Wojnarowicz 2000; Huvaj-Sarihan and Stark 2008). The unit weight of the waste material was 17 kN/m^3 (because the waste is mixed with demolition debris) and the natural water content of the waste is 28–80%. The groundwater/leachate level is 3–5 m below ground surface. No geosynthetic liner system was installed prior to waste placement and thus the waste is in contact with native materials and groundwater. Thus, the groundwater level corresponds to the leachate level. The slope did not experience a large slide but tension cracks developed in buildings on top of the landfill indicating the onset of sliding. Some of the observed building cracks may be caused by waste settlement rather than slope movement but tension cracks were observed indicating the onset of instability. Because the slope did experience extensive movement, the FS was assumed to be near unity for the back-analysis. To back-calculate an effective stress

Table 2 Summary of MSW landfill case histories used to back-calculate MSW shear strength

Label in Figs. 5 and 6	Reference	Maximum landfill height (m)	Average effective stress along failure surface in waste (kPa)	Average leachate level in terms of Pore Pressure ratio[a]	Back-calculated shear stress (kPa)
NJ	New Jersey site (Oweis and Khera 1998); Dvinoff and Munion 1986)	23	62	0.065	46
M	Maine site (Richardson and Reynolds 1991)	27	34	0.045	35
C	Cincinnati site (Eid et al. 2000)	84	90	0.078	103
EO	Eastern Ohio site (Stark et al. 1998)	24.5	35	0.021	29
W	Warsaw site, Poland (Bouzza and Wojnarowicz 2000)	26	106	0.44	40
DJ	Dona Juana, Columbia (Hendron et al. 1999, Gonzalez-Garcia and Espinoza-Silva 2003; Fernandez et al. 2005; Hendron 2006)	60	55	0.15–0.80	34
P	Payatas, Phillipines (Merry et al. 2005)	33	95	0.43	69.5
H	Hiriya landfill, Israel (Isenberg 2003)	60	32	0.65	46
IS	Istanbul landfill, Turkey (Kocasoy and Curi 1995)	45	65	0.50	72.5
BR	Cruz das Almas Landfill, Brazil (Gharabaghi et. al 2006)	40	28.9	0.30	20.3
IN	Leuwigajah dumpsite, Indonesia (Koelsch 2005)	70	31.2	0.21	86

[a] Pore pressure ratio, $r_u = u/\gamma h$

friction angle, the MSW was assumed to exhibit a c' of 0 kPa. The back-calculated ϕ' is 21°. The back calculated friction angle is reasonable considering the age of the waste. The landfill is estimated to be 300 years old (Bouzza and Wojnarowicz 2000). Therefore, the back-calculated shear strength of MSW is expected to be comparable to the shear strength of a cohesive soil. The average normal stress on the observed failure surface through the waste is 106 kPa.

Another landfill analyzed was located in Istanbul, Turkey. The dumpsite has been in operation since 1976. Composition of the waste material, after removal of the recyclable material by scavengers, is estimated to be about 70% food remains/organics, 10% papers, 6% textile, 3% plastics, 3% metals (Kocasoy and Curi 1995). Maximum MSW slope height was about 45 m, with steep front slopes of up to 45° or even more. The MSW was placed without any liner system. The waste is not compacted and is not covered with soil. The catastrophic slope failure occurred in 1993 and included up to 1,000,000 m^3 of waste. Pictures taken after the failure and the cross section used in slope stability analyses are shown in Huvaj-Sarihan and Stark (2008). Heavy rains, and excessive leachate level built up within the old decomposed waste were likely the triggering mechanism, together with recently placed demolition debris on top of the waste (Kocasoy and Curi 1995). An MSW unit weight of 11 kN/m^3 is assumed because no further information is available. The average normal and shear stresses on the observed failure surface through the waste is 65 and 72.5 kPa, respectively.

The Hiriya waste dump is located in Tel-Aviv, Israel, and was in use from 1952 to 1998 (Isenberg 2003). The landfill reaches a height of 60 m above the surrounding level ground, with the slopes of 45° or more. The landfill does not have an engineered bottom liner, final cover, or leachate and gas control systems. Side slopes of Hiriya landfill range from 1.3H:1 V to 1.6H:1 V. As a result of the steep slopes, the lack of drainage and erosion controls, the landfill has experienced small and large instability problems. In 1997 a major slope failure occurred following a period of heavy rain. Pictures taken after the failure and the cross section used in slope stability analyses are shown in Huvaj-Sarihan and Stark (2008). The average normal and shear stresses on the observed failure surface through the waste is 32 and 46 kPa, respectively.

The unit weight of MSW is an important parameter in engineering analyses of landfill performance, but significant uncertainty currently exists regarding its value (Zekkos 2005). There was not enough information to model the change in unit weight with depth in the back analysis of these landfill slope failures.

Conclusions

The following conclusions can be discerned concerning the shear strength of MSW:

1. Shear strength of MSW depends on many factors, such as, waste type, composition, compaction, daily cover material, moisture conditions, leachate management, age and overburden pressure and these factors should be considered in the design process.
2. Laboratory or in situ shear strength data should reflect the level of shear displacement or axial strain that corresponds to the reported shear strength value because MSW shear resistance usually increases with increasing displacement/strain. This trend is more pronounced in triaxial compression than direct shear testing results.
3. It is recommended that a shear displacement greater than 60 mm or an axial strain of greater than 20% be used in MSW shear testing to mobilize a shear resistance that may be representative of the peak shear strength of MSW.
4. The peak shear strength of MSW is high as evident from at or near vertical landfill slopes or scarps that remain stable for a considerable time. As a result, testing and stability evaluations should focus on the materials underlying the MSW, e.g., underlying geosynthetics and native soils, unless a weak, continuous layer of waste is present.
5. MSW shear strength is normal stress dependent. It is recommended that a bilinear strength envelope be used to represent the shear strength at high normal stresses. For normal stresses less than 200 kPa, shear strength parameters of $c' = 6$ kPa and $\phi' = 35^\circ$ and for normal stresses greater than or equal to 200 kPa, $c' = 30$ kPa and $\phi' = 30^\circ$ are recommended. The recommended bilinear envelope is based on shear strength data corresponding to a shear displacement of 25 mm or 10% axial strain and thus should be compatible with the shear behavior of underlying geosynthetic interfaces and foundation soil. However, considerable judgment should be used when implementing this strength envelope in a stability analysis because additional data is needed to refine this envelope.
6. Future research on the shear strength of MSW should include more laboratory testing and back-analyses of landfill failures to further refine the MSW shear strength parameters proposed herein.

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