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Application of continuous normal–lognormal bivariate density functions in a sensitivity analysis of municipal solid waste landfill

Igor Petrovic [a,*], Ivan Hip [a], Murray D. Fredlund [b]

[a] University of Zagreb, Faculty of Geotechnical Engineering, Hallerova aleja 7, 42000 Varazdin, Croatia
[b] SoilVision Systems Ltd., 202-640 Broadway Avenue, Saskatoon, SK, S7N 1A9, Canada

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ABSTRACT

The variability of untreated municipal solid waste (MSW) shear strength parameters, namely cohesion and shear friction angle, with respect to waste stability problems, is of primary concern due to the strong heterogeneity of MSW. A large number of municipal solid waste (MSW) shear strength parameters (friction angle and cohesion) were collected from published literature and analyzed. The basic statistical analysis has shown that the central tendency of both shear strength parameters fits reasonably well within the ranges of recommended values proposed by different authors. In addition, it was established that the correlation between shear friction angle and cohesion is not strong but it still remained significant. Through use of a distribution fitting method it was found that the shear friction angle could be adjusted to a normal probability density function while cohesion follows the log-normal density function. The continuous normal–lognormal bivariate density function was therefore selected as an adequate model to ascertain rational boundary values ("confidence interval") for MSW shear strength parameters. It was concluded that a curve with a 70% confidence level generates a "confidence interval" within the reasonable limits. With respect to the decomposition stage of the waste material, three different ranges of appropriate shear strength parameters were indicated. Defined parameters were then used as input parameters for an Alternative Point Estimated Method (APEM) stability analysis on a real case scenario of the Jakusevec landfill. The Jakusevec landfill is the disposal site of the capital of Croatia – Zagreb. The analysis shows that in the case of a dry landfill the most significant factor influencing the safety factor was the shear friction angle of old, decomposed waste material, while in the case of a landfill with significant leachate level the most significant factor influencing the safety factor was the cohesion of old, decomposed waste material. The analysis also showed that a satisfactory level of performance with a small probability of failure was produced for the standard practice design of waste landfills as well as an analysis scenario immediately after the landfill closure.

1. Introduction

The main geotechnical design issue of the sanitary landfills involves the assessment of global stability. Stability must be ensured within the exploitation period and also in the aftercare (post closure) period. The design considerations should include the stability of the waste material, liners, leachate and gas collection and removal systems, as well as the stability of the foundation soils to ensure long term stability of waste landfill. The design of a landfill must consider the geometry of the design section, the strength parameters of main materials and the possible influence of pore-water pressures.

Conventional approaches to slope stability problems involve the solution of equilibrium equations of force and moment. This is traditionally accomplished through method of slices techniques or more progressive stress-based methods (Petrovic et al., 2006). Uncertainties linked with input variables, such as shear strength parameters of waste material, can result in uncertainty in the computed factor of safety.

Probabilistic stability analysis has become a popular tool for the estimation of the safety level associated with geotechnical slopes. The application of probabilistic approach to slope stability problems has been widely encouraged during the past three decades by many researchers (Ang and Tang, 1975; Vanmarcke, 1974; Whitman, 1984, 2000; Harr, 1987; Christian et al., 1992; Becker,

* Corresponding author.
E-mail addresses: igor.petrovic@gfv.hr (I. Petrovic), ivan.hip@gfv.hr (I. Hip), murray@soilvision.com (M.D. Fredlund).

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1996a, 1996b; Duncan, 2000). In the case of landfills where uncertainties of solid waste strength parameters are very high, the use of probabilistic methods has increased attraction.

Probabilistic approaches require characterization of the variability of material properties and this can be done using conventional statistical methods. The variability of untreated MSW shear strength parameters, namely cohesion and shear friction angle, are of primary concern in this paper. A large number of (pairs of) MSW shear strength parameters were collected to determine statistical properties for a probabilistic analysis in the present study. Rational boundaries were also established for the shear strength parameters.

The uncertainties of waste shear strength parameters are high in the case of landfills. Consequently, a sensitivity analysis is useful to make a distinction between critical and less vital input parameters when calculating the factor of safety.

A statistical analysis conducted on collected data showed that shear strength parameters are negatively correlated. Even though the computed correlation between the shear friction angle and cohesion was not strong, it was still significant.

The use of a distribution fitting method revealed that the shear friction angle can be adjusted to that of a normal probability density function while cohesion follows the lognormal density function. It was concluded that a continuous normal–lognormal bivariate density function (Chen, 2002) could provide an adequate model to ascertain rational boundary values for the shear strength parameters. The statistical designations fit well into the Alternative Point Estimated Method (APEM).

Based on the suggested ranges of shear strength parameters, the APEM analysis conducted on a real case scenario showed the most significant influence on the safety factor was the shear friction angle of old, decomposed waste material. Furthermore, the analysis also showed that for the commonly accepted design of waste landfills, immediately after the landfill closure, a sufficient level of performance can be anticipated with a small probability of failure.

2. Shear strength parameters collected from published literature

Table 1 presents residual shear strength parameters collected from the available literature. Presented data includes parameters obtained with different experimental techniques such as direct shear tests, simple shear tests, back-analysis, and in few cases even an estimated values.

In the last few years several researchers (Zhu et al., 2003; Zhan et al., 2008; Karimpur-Fard et al., 2011; Zekkos et al., 2012; Jie et al., 2013) have also published shear strength parameters obtained using triaxial tests. Attempts to include this data in the statistical analysis proved to be futile owing to the large dispersion in the collected data. It could be argued that the main reason for the large dispersion was related to the fact that strength testing

Table 1
Shear strength parameters collected from the available literature.

Reference	Age of waste samples	Cohesion (kPa)	Friction angle (°)	Testing device	Additional comments
Bray et al. (2009)	/	15	36	LDS	/
Caicedo et al. (2002)	1 year	78	23	LDS	/
Cho et al. (2011)	Fresh	17	36	LDS	0% f.w.c.
	Fresh	37	26	LDS	40% f.w.c
	Fresh	24	24	LDS	58% f.w.c.
	Fresh	4	15	LDS	80% f.w.c.
Cowland et al. (1993)	/	10	25	BA	/
Dixon et al. (2008)	/	0	33.9	LDS	Synthetic waste
Eid et al. (2000)	/	25	35	/	Estimated values
Greco and Oggeri (1993)	Fresh	<5	38–42	/	Loose state
	Fresh	30–50	38–40	/	/
	Degraded	5–15	23–27	/	/
	Degraded	16–32	19–24	/	/
	Degraded	0–10	17–23	/	/
Hossain et al. (2009)	/	0	32	DS	(C + H)/L = 1.29
	/	0	27	DS	(C + H)/L = 1.29
	/	0	26.5–28.2	DS	(C + H)/L = 0.73
Houston et al. (1995)	/	5	33–35	LDS	/
Howland and Landva (1992)	10–15 years	17	33	LDS	/
Jie et al. (2013)	3–18	22	31	SS	/
	3–18	55	24	SS	/
	3–18	21	35	SS	/
	3–18	37.5	34	SS	/
	3–18	40	30.3	SS	/
	3–18	30	36.4	SS	/
	3–18	50	35.4	SS	/
	3–18	25	38.1	SS	/
Jones and Dixon (2003a)	/	5	25	/	Estimated values
Kavazanjian (2001)	/	43	26	DS	/
	/	0	39	DS	
	/	17	33	SS	/
	/	19	28	BA	/
Kölsch (1993)	Fresh	0	26.4	DS	/
	Old	0	17.7	DS	/
Landva et al. (1984)	Fresh	16	40	LDS	/
	1 year	16	33	LDS	/
	Fresh	23	24	LDS	Shredded
	/	10	33.6	LDS	Woodwaste
Mazzucato et al. (1999)	/	24	18	In situ	Undisturbed
	/	22	17	LDS	Disturbed