ORIGINAL PAPER

Rehabilitation of Saravan dumpsite in Rasht, Iran: geotechnical characterization of municipal solid waste

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Abstract

Accepting and landfilling municipal solid waste, MSW, in non-engineered conditions since 1984, has made the Saravan dumpsite as one of the biggest environmental concerns in northern Iran. Due to a lack of any type of coverage, precipitation is infiltrated into the waste piles, increasing the amount of leachate production. The average annual discharge rate of leachate is estimated to be 7 L per second, which all are discharged to the downstream rivers and creeks. To reduce the produced leachate, the construction of soil cover, leachate drainage system, gas collection systems and other requirements were planned. To construct the soil cover, stability analyses to reach a safe side slope were necessary; therefore, geotechnical evaluation of MSW was vital. MSW samples with different age and conditions were collected, and geotechnical tests such as moisture and organic content, composition, grain size distribution and direct shear tests were performed. Back-calculation analyses performed on unstable slopes at the site resulted in situ shear strength of MSW, comparable with those achieved in laboratory tests. Results showed that the soil-like fraction, moisture and organic content decrease with depth and age, leading to an increase in foil-like contents and reduction in shear strength of MSW. Direct shear tests with different shearing rates showed that the MSW in Saravan dumpsite exhibits higher strength at higher rates of shearing which means a higher safety factor for slopes during seismic condition could be expected.

Keywords Leachate · Municipal solid waste · Saravan dumpsite · Shear strength · Stability analysis

Introduction

Waste slope stability is one of the major concerns associated with landfills during their operation, after their closure or in case of development and expansion. Potential slides in the waste mass can result in the movement of large volumes of waste, bringing about disastrous consequences such as fatalities, damages to infrastructures and irrecoverable environmental outcomes. The failure of the Payatas landfill in the Philippines with at least 278 casualties is one of such catastrophes (Zekkos 2005). Obtaining information about the mechanical behavior of municipal solid waste (MSW) and conducting stability analyses based on

this information is a necessary step in the prevention of the aforementioned incidents. Shear strength parameters of the MSW are required for conducting stability analyses since failure usually happens entirely or partially within the waste mass. Shear strength and mechanical behavior of MSW have been investigated by several researchers like: Landva and Clark (1986), Gabr and Valero (1995), Kavazanjian et al. (1995), Manassero et al. (1996), Jones et al. (1997), Van Impe (1998), Kavazanjian (1999), Eid et al. (2000), Caicedo et al. (2002a, b), Zekkos et al. (2005), Karimpour-Fard (2009), Bray et al. (2009), Shariatmadari et al. (2017), Asadi et al. (2017), Ramaiah et al. (2017), Ramaiah and Gunturi (2017) and many others. As the compositional and physical properties of MSW vary widely among regions based on the community's lifestyle and consumption culture, the food regime, the economy and weather conditions, the importance of site-specific stability analyses becomes pronounced. The effect of waste degradation on the shear strength of MSW and aging also is an important factor in the assessment of landfill stability. The possible reduction of shear strength as a result of waste decomposition is an important concern

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in the long-term stability of a landfill; however, opposing results have been reported on the effect of waste decomposition on MSW shear strength in the literature. Van Impe (1998) and Harris et al. (2006) reported an elevated shear strength in the aged MSW samples compared to the fresh samples. It was claimed that this increase is attributed to the higher fiber content in the aged MSW as a result of the mass loss in organic fractions in MSW. Gabr et al. (2007), and Hossain and Haque (2009) reported a decrease in the shear strength of MSW as a result of waste decomposition. However, Karimpour-Fard et al. (2014) showed that the evolution of shear strength of MSW is dependent on the applied shearing mechanisms and the type of shearing device employed for testing: shear strength increases in the triaxial testing apparatus while reducing in samples tested in the direct shear test device due to fiber orientation. According to Bareither et al. (2012), waste composition, moisture and organic content are also important factors that can influence the rate of waste degradation and the corresponding shear strength and explain part of the contradictions reported concerning aging effect. They reported in direct shear tests an increasing content of soil-like, gravel and the inert waste increases the waste friction angle, while an increasing content of plastic, paper or cardboard reduces it due to their lower friction angle, which means a lower friction angle in aged waste could be expected. However, in MSW with a large content of inert material or daily cover soil, the friction angle can increase as a result of aging due to the mass loss that occurred in the organic parts.

Little research has been conducted on the mechanical behavior of MSW in landfills of Iran. The landfill of Saravan, located in Guilan, is the largest landfill in northern Iran. Once a temporary dumpsite, it has since become the main dumpsite for the city of Rasht as well as multiple nearby towns due to the ever-growing population and massive generation of waste. Saravan landfill as the largest non-engineered dumpsite in the area has been the main source of soil and water pollution in the region. The problems and difficulties associated with this pollution faced by the local people have in turn exerted a considerable social pressure on the local authorities. As a result, the municipality of Rasht has decided to start a rehabilitation project on the Saravan dumpsite with the aim of minimizing the pollution of air, soil and water by collecting and treating the leachate before discharge into downstream.

This paper deals with activities performed in this project in the first phase, including preliminary investigation of the dumpsite, field and laboratory evaluation and stability analysis, which will be presented in the next sections.

Landfill site

The Saravan landfill (37°4′17.94″N; 49°37′52:70″L) was established in 1984 as a temporary dumpsite with an area of about 12.5 ha. Since then, it has become the biggest landfill in northern Iran and the only dumpsite for the generated waste from the city of Rasht, Fouman, Shaft, Some' Sara, Khoshke Bijar, Lashte Nesha, Kouchesfehan and Anzali. In Fig. 1, a view of the Saravan landfill is presented. In this figure, the variation of slopes in this dumpsite is also depicted in percentages to help evaluate the landfill's slopes.

At present, the landfill receives about 700 tons MSW/day. The large and steady stream of waste dumped at the site has led to a pile-up of waste as high as 70 m.

Due to the lack of the final cover liner, most of the average annual precipitation of 1200 mm infiltrates into

120 - 100	75 - 62	50 - 38	25 - 18	12 - 5
100 - 75	62 - 50	38 - 25	18 - 12	5 - 0
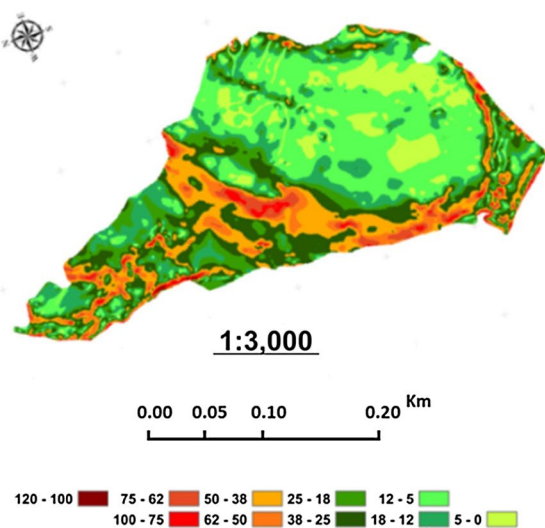
Fig. 1 A view of Saravan landfill and slope classification

Fig. 2 Leachate flow to downstream

Table 1 Chemical characterization of leachate in Saravan dumpsite

No.	Parameter	Unit	Permissible value	Measured value
1	Iron	mg/L	3	3.55
2	Cu	mg/L	1	2.084
3	Zn	mg/L	2	2.216
4	Hg	µg/L	0	6
5	Cl^-	mg/L	600	3040
6	SO_4^{2-}	mg/L SO_4	400	560
7	PO_4^{3-}	mg/L PO_4 as P	6	28.8
8	TKN	mg/L	13	6199
9	COD	mg/L	60	10,732
10	BOD5	mg/L	30	6242
11	TSS	mg/L	40	392
12	TDS	mg/L	500	4180

the MSW body and a large amount of waste-contaminated water and leachate flows downstream to the nearby rivers and lagoons. Preliminary analysis performed based on the HELP model Schroeder et al. (1994) estimated an average discharge rate of leachate of 600 m³/day, with a peak discharge rate of about 2000 m³/day. In Fig. 2, a stream of leachate from Saravan landfill moving downstream can be observed.

Needless to say, the produced leachate is a hazardous material which contains a considerable amount of heavy metals and toxic materials and compounds.

As an illustration of the environmental impact caused by the lack of cover and bottom liners and leachate collection systems, Table 1 presents the results of leachate analysis of the Saravan dumpsite along with the maximum admissible value according to Iranian Engineering Standards for Water Pollution Control (2005). The results of analysis show that produced leachate does not meet the regulations and must be collected and treated.

Materials and methods

In order to analyze the stability of the waste mass, an evaluation of the main MSW physical and mechanical properties is necessary. Samples of different age were obtained from several locations and depths with the use of a rotary boring excavator (80 cm diameter). The location of the boreholes was chosen to be close to locations where past instability had occurred. Physical properties of the MSW samples were investigated by performing a compositional analysis as well as obtaining the moisture content, organic content and conducting grain size analysis on the samples. Large-scale static and dynamic direct shear tests were conducted to examine the mechanical behavior of the MSW specimens. Besides that, back-calculation analyses were performed in three slopes in the vicinity of the performed boreholes using the finite element program Plaxis 2D. These slopes had previously been subjected to instability with large movements in the waste body. Using the results of laboratory testing and back-calculations, the stability analysis of four other slopes was also executed.

Sampling

Sampling campaign was based on the historical information of waste disposal at the site. Figure 3 shows the location of the boreholes (green circles) on the topographic map of site along with the instabilities observed in the side slopes (blue circles). The red lines represent the slope sections chosen for slope analysis. In this figure, the depths of sample retrieval for each borehole are also depicted. For the same borehole, depth of each sample is linked to its age in way that samples obtained from shallower depths correspond to newer and supposedly less decomposed MSW. About 70 kg of MSW was collected for each depth. This amount was enough to perform the series of tests to be conducted. Upon retrieval, samples were put in the plastic bags, protected by plastic barrels and transferred to the laboratory. The waste was kept in a cool place to avoid any further decomposition. Figure 4 shows the MSW sampling sequences in the project.

Laboratory testing method

Samples taken from different depths at each borehole were used to determine the waste composition, the grading, water content, organic content and pH. Samples were also used as part of large-scale static and cyclic direct shear tests to determine the shear parameters of the MSW.

Compositional analysis of MSW

A compositional analysis was performed in order to determine the MSW main constituents of the samples obtained
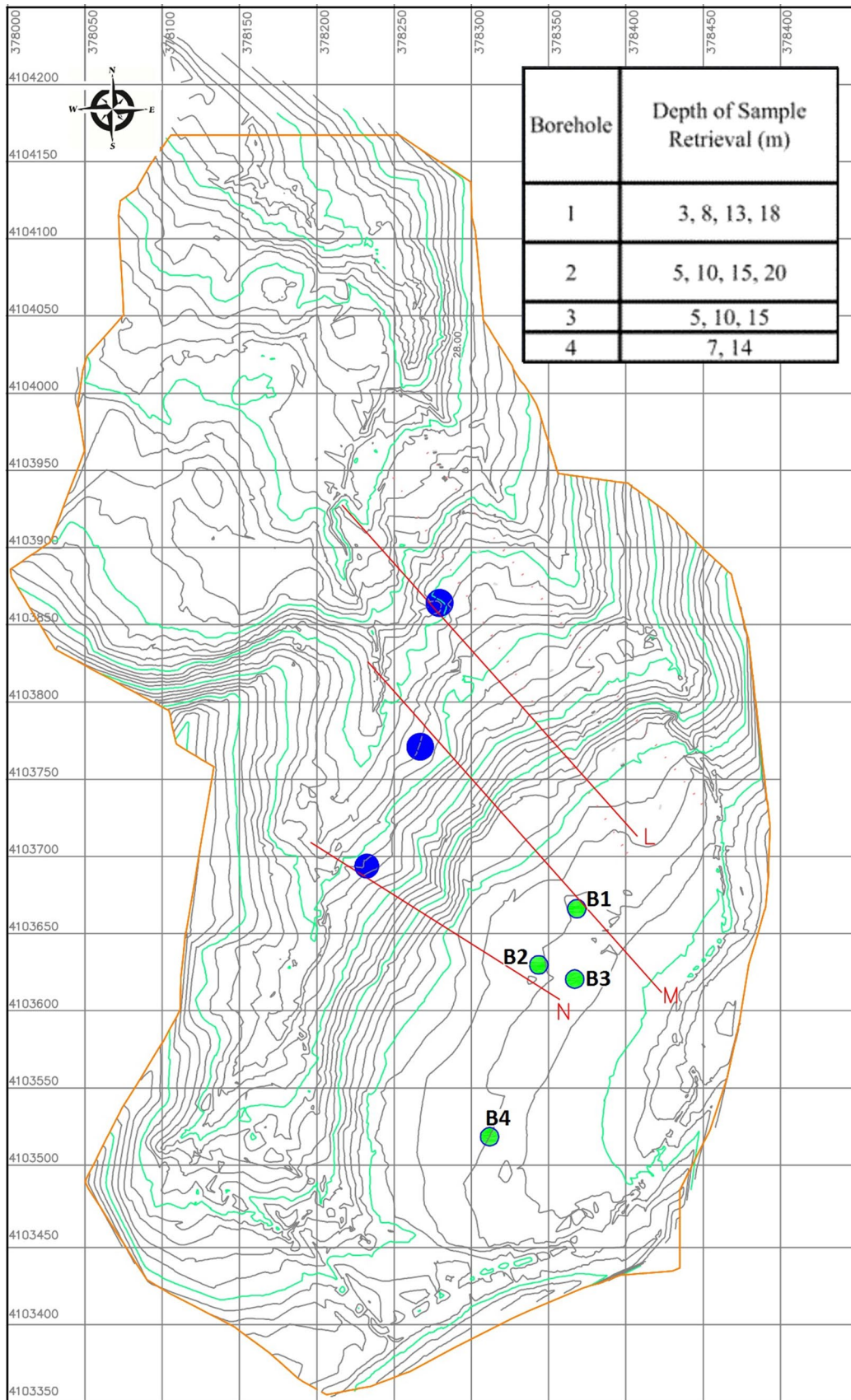
Fig. 3 Topographic map of the Saravan dumpsite

Fig. 4 Sampling sequences of MSW in Saravan dumpsite project

from each borehole. This procedure was accomplished by the visual inspection of the waste and segregation of the major constituents. The fraction of each component was then measured based on wet weight. The waste constituents were separated into the following categories: plastic, paper and cardboard, glass, metal, wood, textile, rubber and leather, rock and ceramic and paste. The paste fraction refers to organic waste, soil and other soil-like material that could not be easily separated.

Grain size analysis

In order to obtain the grain size distribution curves, 20 kg portions of each MSW sample were first oven-dried at °C until mass stabilization. Then, sieve analyses were performed employing sieves with opening sizes of 0.15–101 mm. Particles larger than 101 mm were separated and had their sizes measured with a ruler.

Moisture content

In order to obtain the moisture content of the MSW samples, 5 kg from each sample was stored in the oven for 48 h at a temperature of 70 °C. The sample weight was measured at every 12 h until the difference between the two readings was lower than 1%. Moisture content was then calculated based on dry weight.

Organic content

The organic content of MSW is evaluated using a variety of methods and a number of parameters in the literature. Total organic carbon, total volatile solids (TVS) and cellulose + hemicellulose to lignin ([C + H]/L) are some of these parameters. In this research, the following procedure was adopted to obtain the TVS value as a measurement of MSW's organic content.

After sieving the waste, 1000-g samples of the paste fraction were collected and ground in order to reduce the size of the particles and increase the specific surface of the specimens. Then, 20-g portions of these specimens were placed into the crucibles and dried in an oven at 70 °C for 1 h. The samples were then combusted in a muffle at 600 °C for 2 h. The volatile content was computed as the ratio between mass loss and the dry mass before combustion.

Shear strength tests

Reconstituted specimens were prepared for large-scale static and cyclic direct shear tests with a shearing box of 30×30 cm and a height of 18 cm, powered with a 2.2-kW servomotor. The lower part of the box has a height of 7.5 cm and the upper part 10.5 cm to prevent the test results from being affected by the proximity of the loading plate to the shearing plane at high levels of normal stress due to the considerable settlement of MSW. A "S"-shaped load cell capable of measurements in both compression and tension was utilized to measure the applied shear stress in two-way shearing tests and to evaluate the shear strength of MSW in cyclic loading condition. The applied shearing rate of the employed apparatus varies in a range of 0.5–12 mm/min.

Material larger than one-sixth of the sample dimensions was removed during the placement of MSW inside the shearing box as suggested in ASTM D3080/D3080M. MSW samples were compacted in three layers in the shearing box to reach a density of 12 kN/m³, and the consolidation phase was started till the negligible settlement of the upper cap was observed. The samples were tested at three levels of normal stress, namely 50, 100 and 200 kPa. After the completion of the consolidation phase, samples were sheared at a shearing rate of 0.8 mm/min which is comparable with Karimpour-Fard et al. (2014), Zekkos (2005) and Jones et al. (1997). Each sample was sheared up to 15% of the sample length.

In order to evaluate the effect of shearing rate on the shear strength of MSW materials, several samples were sheared under different shearing rates. The results of these tests were employed to calculate the rate dependency coefficient of MSW shear strength.

Results and discussion

Waste composition

Figure 5 shows the fraction of each component for the samples obtained from two different depths at the fourth borehole (wet basis).

It can be seen that paste, plastic, rock and ceramic and paper and cardboard are, in this order, the most abundant components. For geotechnical purposes, the MSW composition was also classified into two general categories: soil-like (bulky constituents, soil and paste) and foil-like materials, which includes all the constituents with reinforcement effects such as plastic, textiles, rubber and paper.

Figure 6 shows the variation of soil-like and foil-like content of MSW with depth. Despite some scattering, foil-like components tend clearly to increase with depth, the opposite occurring with the soil-like components. Figure 7 shows the variation of MSW composition in São Carlos landfill, Brazil, as reported by Abreu and Vilar (2017). Number after "S" means the estimated year of MSW landfilling. "F" means as recovered (without the removal of large particles) MSW and "T" as tested waste (Abreu and Vilar 2017). As it can be noted, the composition of the "F" samples shows that soil-like components predominate in all samples, followed by soft plastics, the second most abundant component, varying from 13.2 to 27.3%. Both components show no trend regarding landfilling age.

According to Abreu and Vilar (2017), however, no clear tendency between landfilling age and the degradation of the samples could be established in their study, the MSW samples being grouped as "well degraded waste." This could be the reason for the differences observed between the São Carlos and Saravan dumpsites, since in the case of Saravan
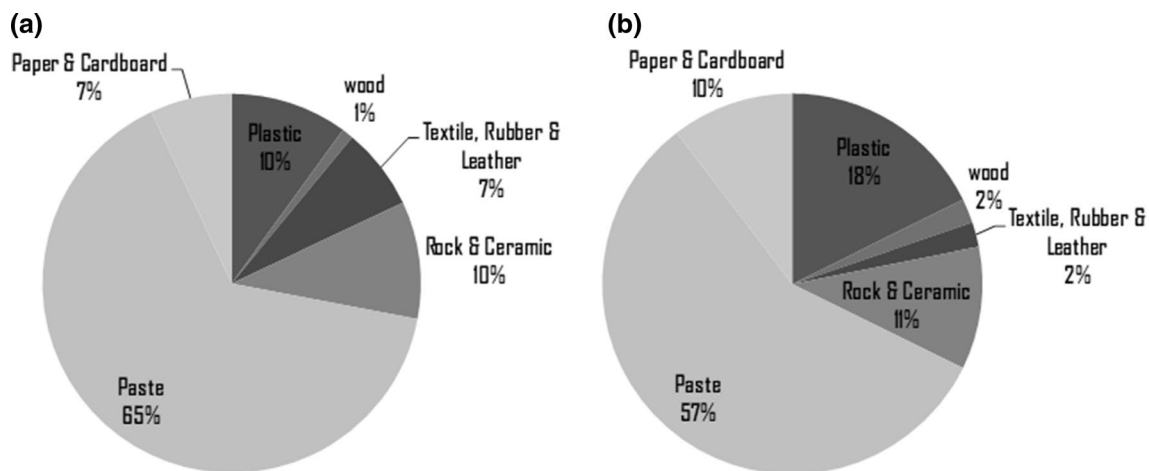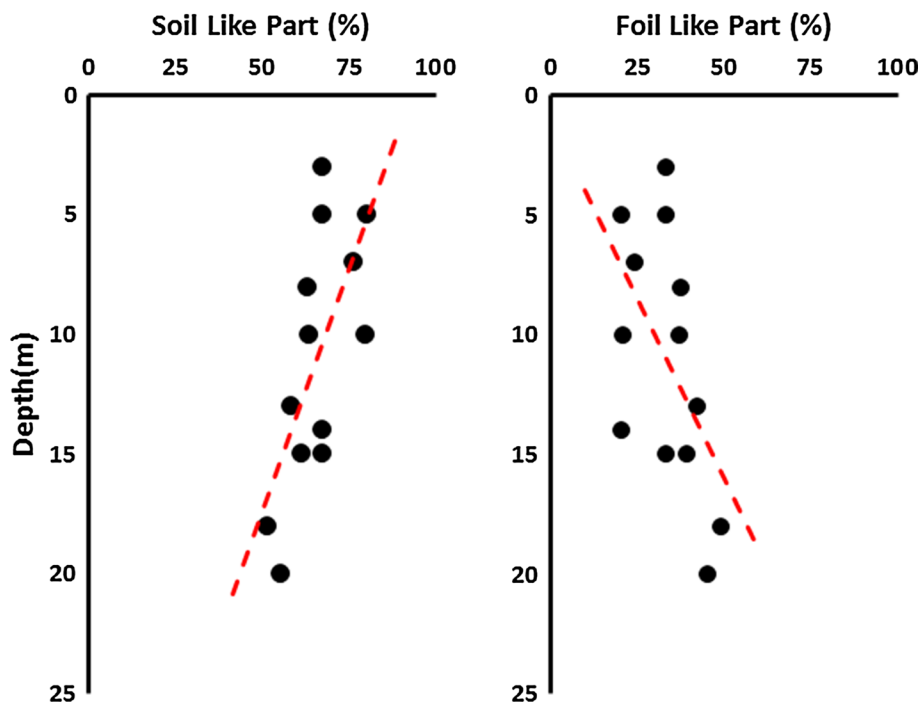

Fig. 5 Composition of samples retrieved from B4 and depth **a** 7 m, **b** 14 m
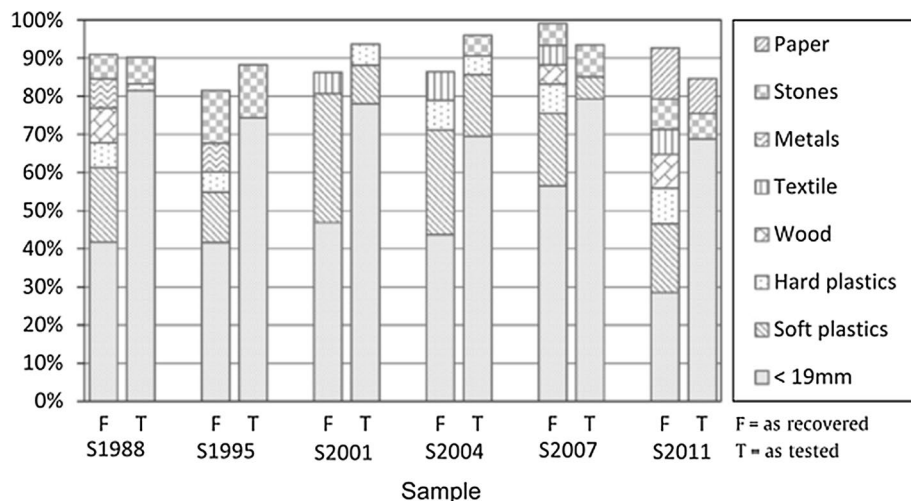
Fig. 6 Variation of soil-like and foil-like content with depth in the Saravan dumpsite

Fig. 7 Variations of MSW with age (after Abreu and Vilar 2017)

dumpsite the progress of decomposition with age/depth is clear.

Grain size analysis

Figure 8 shows the results of grain size analysis conducted on the MSW samples. Grain size distribution curves were first obtained for all the samples individually. Based on these curves, average curves for depths of 0–5, 5–10, 10–15 and 15–20 m are presented. The upper and lower ranges for MSW grain size distribution suggested by Jessberger (1994) can also be seen in this figure. A clear trend of size reduction with the depth of sample retrieval could be observed. It

could be concluded that as a result of decomposition, aged MSW materials exhibit a finer grain size. This is in accordance with previous results presented by Machado et al. (2010), Landva and Clark (1986).

Moisture and organic content

Figure 9 shows the variation of the MSW moisture content with depth. Almost all of the samples had a moisture content in the range of 20–60%, and a clear trend of moisture content reduction with depth can be observed. According to Machado et al. (2010) and São Mateus et al. (2012), some of the MSW organic compounds have an excess of water
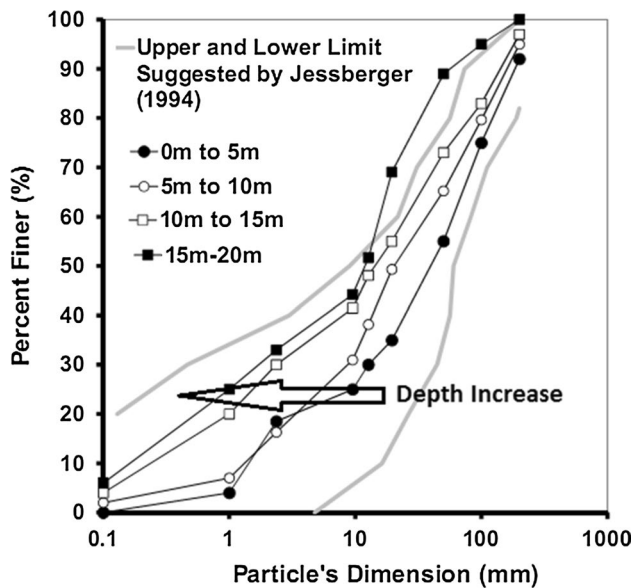
Fig. 8 Grain size distribution curves of the waste at the Saravan landfill
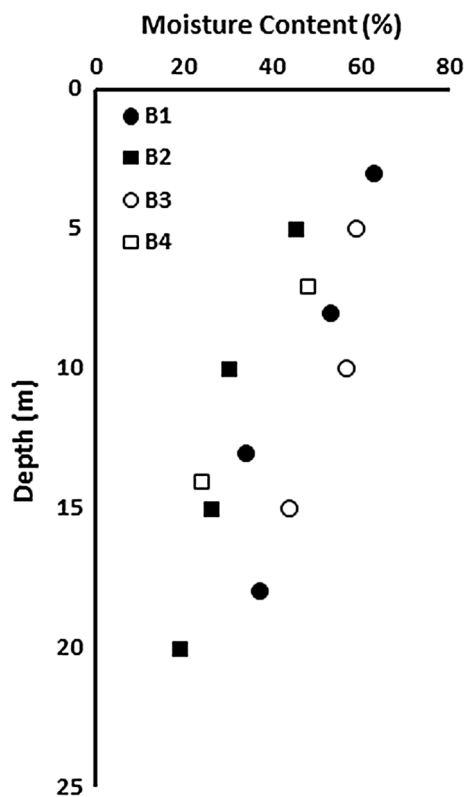
Fig. 9 Variation of MSW water content with depth

compared to the amount of water necessary for biodegradation. This excess of water is released when the component is decomposed. This way, MSW samples located at higher depths in the same borehole (normally more decomposed

waste) tend to present lower moisture contents, unless the decomposition process is not effective in field or the water infiltrate from the landfill surface.

In the present case, the landfill has no cover liner. However, the lack of bottom impervious layers and the steep topography facilitate leachate drainage (see Fig. 2), decreasing the infiltration influence, at least for long-term landfill behavior.

Shariatmadari et al. (2015) evaluated the effect of aging on the physical properties of MSW collected from Kahrizak dumpsite, Tehran, Iran, and also reported a reduction in moisture content with age/decomposition. Moisture content varied from 153% (fresh waste) to 52% (14-year samples).

Figure 10a shows that MSWTVS clearly decreases with depth in the studied MSW samples. Values of TVS of about 50% were found near surface, whereas values of about 25% were found at depth of 20 m. These results are coherent with results published by Shariatmadari et al. (2015) and Machado et al. (2010). Figure 10b shows the variation of the leachate pH with depth. The results show an increase in the pH values with depth and indicate that all tested samples have already passed the acidogenic decomposition stage, since obtained pH values are more consistent with methanogenic/maturation phases (Tchobanoglous et al. 1993).

Shear strength characteristics of the MSW

The main objective of evaluating the shear strength of MSW materials in Saravan was to obtain shear strength envelope for the MSW in this dumpsite to be employed in slope stability analyses.

It should be noted here that MSW is a highly anisotropic material with a pronounced strength anisotropy. Karimpour-Fard et al. (2014) and Shariatmadari et al. (2017) showed that shearing mechanisms affect the mobilization of the shear strength in MSW materials. They showed that the mobilization of the tensile strength of the fibers inside MSW which leads to strain hardening in the mechanical response of MSW is dependent on the alignment of the fibers and their intersection with the shearing plane developed inside the MSW sample (Fig. 11).

Zekkos et al. (2010, 2012) performed several extension and compression triaxial tests as well as direct shear tests on samples with different orientation angle of fibers and reported the anisotropic strength behavior in MSW materials.

As a general rule and according to Matasovic and Kavazanjian (1998), although the waste material is not oriented preferentially when placed initially, the fibrous constituents of the waste tend to become aligned sub-horizontally as a result of compaction and the increasing vertical stress from placing additional waste on top of previously placed waste. The same trend could also be

Fig. 10 Variation of waste organic content and leachate pH with depth
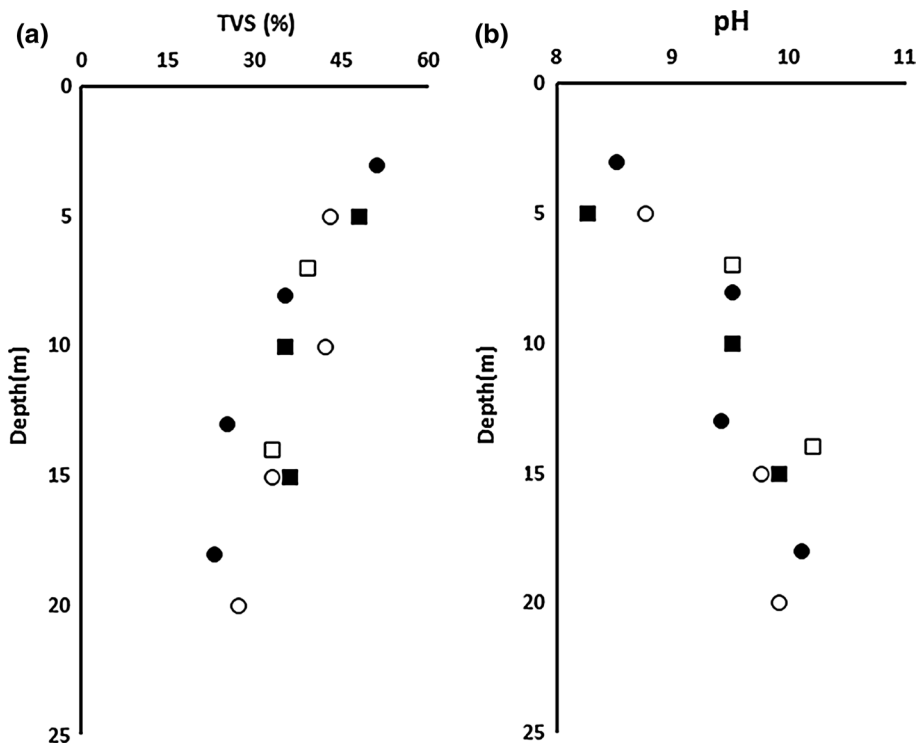
Fig. 11 The difference between the orientation of fibers and the shearing plane in different shearing test devices, **a** triaxial device, **b** direct shear device (after Shariatmadari et al. 2017)
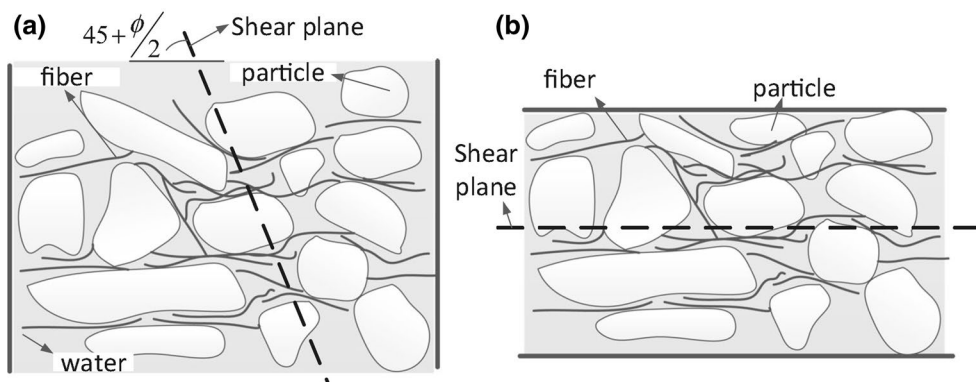

observed in laboratory tests. This means, in the case of direct shear tests, the horizontally aligned fibers in the sample are parallel to the applied shearing plane which leads to only minor reinforcing effect and strain hardening in the mechanical response of MSW materials and therefore, the shear strength envelope will be entitled to a lower limit of MSW shear strength.

In addition to the laboratory testing program with the large-scale direct shear test apparatus, in order to have a better judgment, the location of several instabilities in the form of high deformation and movements in the Saravan dumpsite was identified and the in situ shear strength of MSW was back-analyzed.

Shear strength from laboratory tests

Large-scale direct shear tests were conducted on the samples obtained from different depths to find the shear strength parameters of the MSW and to investigate the variation of shear strength parameters with depth at three normal stress levels of 50, 100 and 200 kPa. The results of direct shear test in the form of internal friction angle and apparent cohesion are presented and compared with reported values in the literature in Fig. 12. This figure was originally developed by Ramaiah et al. (2017) and has been modified to include the results of this research and Abreu and Vilar (2017).

Fig. 12 Comparison of shear strength parameters of MSW achieved in this study with those reported in the literature
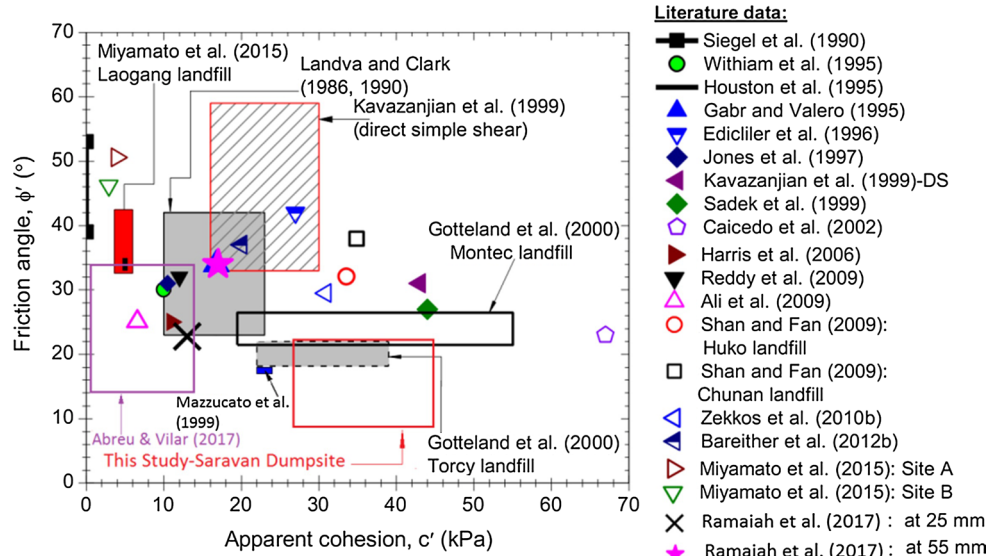
The friction angle of MSW in Saravan ranges from 8° to 22°, whereas the apparent cohesion is in the range of 27–45 kPa. It seems that while the MSW in Saravan exhibits lower values of friction angle which almost fall in the lower range of reported values, the mobilized cohesion of MSW at Saravan is relatively higher compared to the reported values.

Figure 13 shows the results of direct shear tests on samples from borehole No. 4, retrieved from depths of 7 and 14 m.

It can be clearly observed that the shear strength achieved from direct shear tests on MSW samples decreases with depth.

Variation of shear strength parameter with depth, depicted in Fig. 14, suggests that by increasing depth and advancement of decomposition in MSW, both shear strength parameters of MSW decrease which means that

the shear strength of MSW decreases with the advancement of decomposition, the decreasing organic content and soil-like fraction of MSW as well as the increasing foil-like fraction. These results confirm the finding of Landva and Clark (1986), Zekkos et al. (2010), Karimpour-Fard et al. (2014) and Shariatmadari et al. (2017) who suggested the shear strength of MSW tested in direct shear test decreases with aging.

Figure 15 shows the results reported by Bareither et al. (2012), regarding the effects of decomposition on the shear strength of MSW. It can be seen that these results suggest an opposite trend with the trend suggested in this paper, but the results of Gabr et al. (2007) and Hossain and Haque (2009) are in agreement with the reduction of internal friction angle with decomposition.
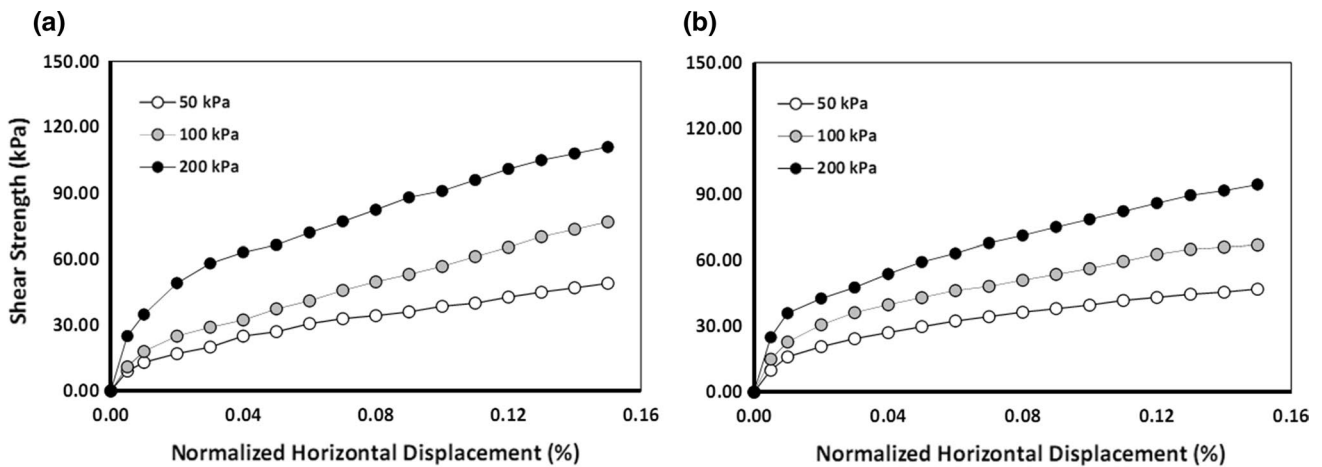
Fig. 13 Results of direct shear test on the sample from B4 retrieved from depth **a** 7 m, **b** 14 m

Fig. 14 Variation of the internal friction angle, cohesion intercept and shear strength of MSW with depth
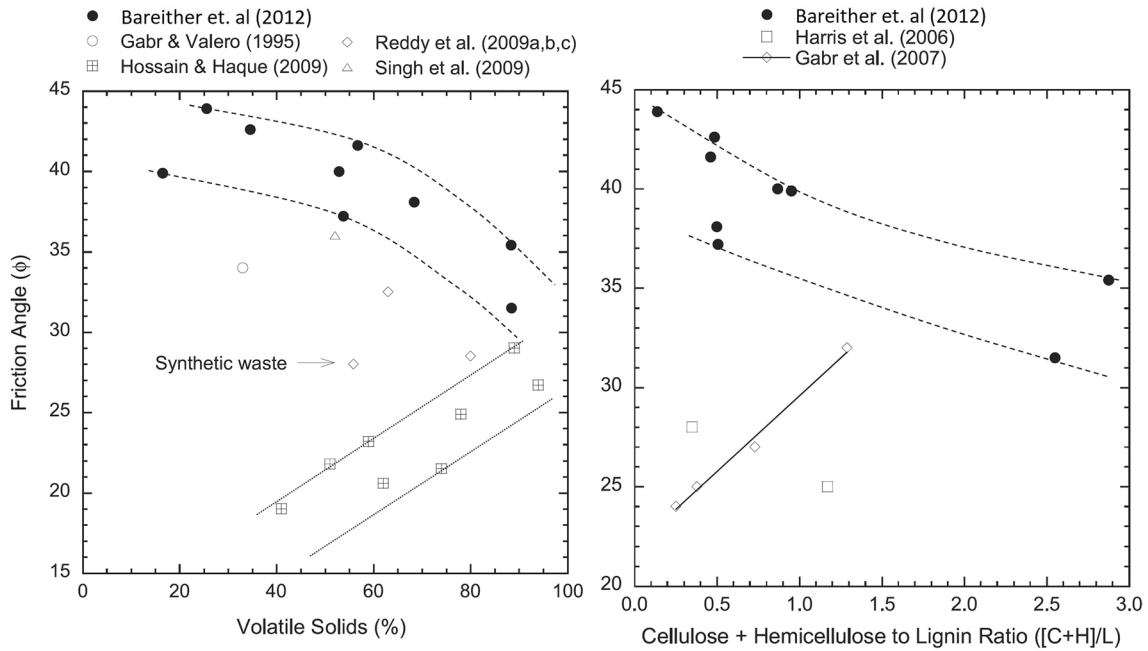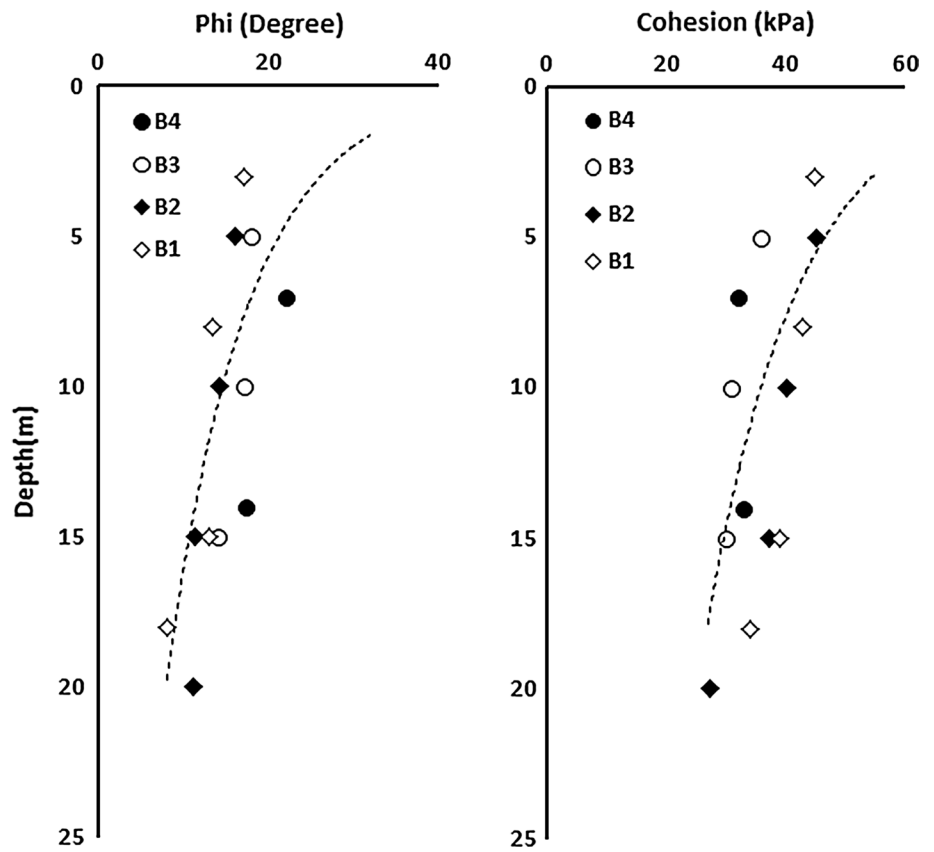
Fig. 15 Effect of decomposition on the variation of internal friction of MSW (after Bareither et al. 2012)

Shear strength from the back-calculation of unstable slopes

Back to Fig. 3, three slopes, marked on the topographic map with red lines, L, M and N, were chosen for back-calculation analysis. As these slopes represent steepest possible slopes, passing to previous instabilities in the dumpsite, they were chosen as alternatives for back-analysis of in situ shear strength of MSW. Slope "M" among chosen slopes was close to largest instability in dumpsite; therefore, it was chosen for this analysis.

To perform a back-calculation analysis on slope M, two main assumptions were made: first a safety factor equal to unity and second assuming a constant value of cohesion for MSW materials and changing the internal friction angle to reach the assumed safety factor. Strength reduction technique (SSR) was employed to execute such back-analysis. In this method, which has been implemented in most commercial finite element and finite difference geotechnical engineering software such as PLAXIS and FLAC, the factor of safety of slope is computed by reducing the shear strength of geomaterials in stages, until the slope fails. For Mohr–Coulomb materials, shear strength is reduced by FS according to the equation:

$$\frac{\tau}{FS} = \frac{c'}{FS} + \sigma \cdot \frac{\tan\left(\varphi'\right)}{FS} \tag{1}$$

This could be re-written as follows:

$$\frac{\tau}{FS} = c^* + \sigma \cdot \tan\left(\phi^*\right) \tag{2}$$

where $c^* = c'/FS$ and $\varphi^* = \arctan(\tan(\varphi')/FS)$ are the reduced Mohr–Coulomb shear strength parameters. For Mohr–Coulomb materials, the software systematically searches for a critical FS, which brings a previously stable slope to the verge of failure. PLAXIS 2D, a finite element software, was employed in this back-calculation analysis.

Figure 16 compares the shear strength envelopes, developed for MSW by different researchers. As seen, the proposed cohesion intercept for design purpose varies from 6 kPa (Stark et al. 2009) to 25 kPa (Eid et al. 2000); however, Stark et al. (2009) suggested a cohesion intercept of 30 kPa for normal stresses higher than 200 kPa.

The results of direct shear tests performed on MSW in Saravan suggest a range of cohesion intercept from 27 to 45 kPa. Considering the results of direct shear tests from borehole No. 4, B4, which is closest to slope M, an average value of 30 kPa was chosen for the cohesion intercept.

In fact, as this value is based on the results of laboratory direct shear tests, which yield a lower bound on the MSW shear strength due to the minor reinforcing effects of fibers and as this value is close to the upper limit for cohesion intercept proposed by Eid et al. (2000), it is considered reasonable.

Figure 17 shows an example of the stable vertical cuts of MSW in Saravan with their height exceeding 12 m in some locations. Interestingly, analyses based on upper and lower limit analysis, assuming this height as the critical depth, yield a cohesion intercept between 30 and 60 kPa. The unit weight of MSW was chosen equal unity based on the in situ measurements of unit weight.

The back-calculation analyses resulted in an internal friction angle of 15°. Table 2 compares the results of current back-calculation with those reported by Stark et al. (2009).

Based on the results of laboratory tests and this back-analysis, a cohesion of 30 kPa and an internal friction angle of 15° were employed for the modification of the slopes geometry in the construction of liners at Saravan.

Fig. 16 Comparison among different design envelopes of MSW slopes. (Reproduced with permission from Ramaiah et al. 2017)
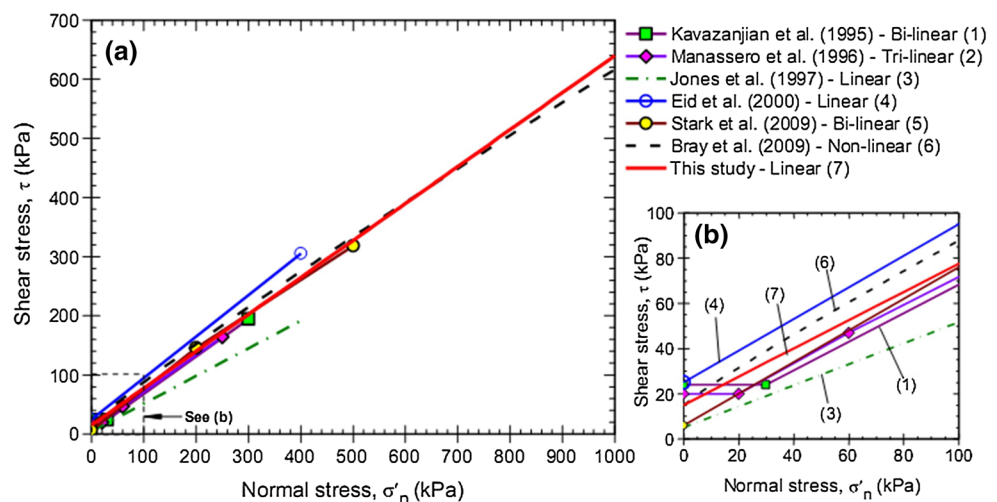
Fig. 17 Vertical cut in the Sara-van dumpsite

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

Landfill	Country	Maximum land-fill height (m)	Average effective normal stress (kPa)	Back-calculated mobilized shear stress (kPa)
New Jersey site	USA	23	62	46
Maine site	USA	27	34	35
Cincinnati site	USA	84	90	103
Eastern Ohio site	USA	24.5	35	29
Warsaw site	Poland	26	106	40
Don Juana landfill	Columbia	60	55	34
Payatas landfill	Philippines	33	95	69.5
Hiriya landfill	Israel	60	32	46
Istanbul landfill	Turkey	45	65	72.5
Cruz da Almas landfill	Brazil	40	28.9	20.3
Leuwigajah dumpsite	Indonesia	70	31.2	86
Saravan dumpsite	Iran	55	110	52

Stability of MSW slopes under dynamic loading

Augello et al. (1995) investigated the seismic performance of several landfills during the 1994 Northridge earthquake. Employing the Kavazanjian et al. (1995) envelopes for unit weight and shear strength recommendations, and the average shear modulus reduction and material damping curves recommended by Kavazanjian and Matasovic (1995) and Vucetic and Dobry (1991) for PI = 200, they reached very interesting results. The authors concluded from their back-analyses that the static friction angle of MSW, for a factor of safety equal to 1.2, varies from 19° to 35°, but the dynamic friction angle for MSW is in the range of 30°–40°. They concluded that the dynamic strength of the waste fill was higher than the shear strength assumed in static stability analyses.

Zekkos (2005) stated from numerical analyses that the strain rate of strong earthquake ground motions is estimated to be approximately 33%/min. To evaluate the rate sensitivity of MSW's shear strength, he performed several triaxial tests using different strain rates. The viscous behavior of MSW showed an increase in the shear strength by increasing the applied shear rate. Based on these results, he suggested that for use in practice, the dynamic shear strength could

conservatively be equal to the static shear strength by a factor of 1.2.

Tatsuoka (2004) proposed the rate sensitivity coefficient (β) to evaluate the viscous behavior of geomaterials as follows:

$$\beta = \frac{\frac{\Delta\sigma}{\sigma_0}}{\log\left(\frac{\dot{\varepsilon}_f}{\dot{\varepsilon}_0}\right)} \quad (3)$$

where $\Delta\sigma$ is the stress increment under the initial strain rate $\dot{\varepsilon}_0$, σ_0 is the total deviatoric stress when the strain rate changed, and $\dot{\varepsilon}_f$ is the final strain rate.

Karimpour-Fard et al. (2011) employed this equation to calculate the rate sensitivity coefficient, β, of MSW. Based on the results reported by Zekkos (2005) and some triaxial tests performed on MSW samples from Metropolitan landfill in Salvador, Brazil with different shearing rate, rate dependency of shear strength of MSW materials was concluded. The average value for β for the results obtained by Zekkos (2005) is around 0.2, while the β values for Karimpour-Fard et al. (2011) were dependent on confining pressure and applied axial strain and ranged from as low as 0.2 to as high as 1.05.

Feng et al. (2016) tested MSW materials collected from Laogang landfill in China and reported the increase in the shear strength of MSW materials with the increase in the shear rate.

To confirm the viscous behavior of MSW in Saravan and the dependency of shear strength on shearing rate, several tests were performed on different samples retrieved from different depths and boreholes with two different shearing rates of 1 and 10 mm/min and β values were obtained. Two normal stresses of 50 and 100 kPa were adopted for these tests.

Figure 18 shows typical results of rate sensitivity tests performed on samples collected from B1 and depth of 3 m as well as variation of β values with depth. It is obvious that MSW samples in Saravan exhibit a clear viscous behavior and shearing rate-dependent response. Increasing the rate of shearing on MSW leads to an elevation in its mechanical response. The β values achieved from these tests ranges from 0.06 to 0.13 which seems to decrease with depth.

These results could confirm the results of Augello et al. (1995) who suggested that MSW slopes stable under static conditions could also be stable under dynamic loading. Therefore, it was concluded that the stability of a slope in Saravan under static condition would probably not be affected during dynamic loading condition.
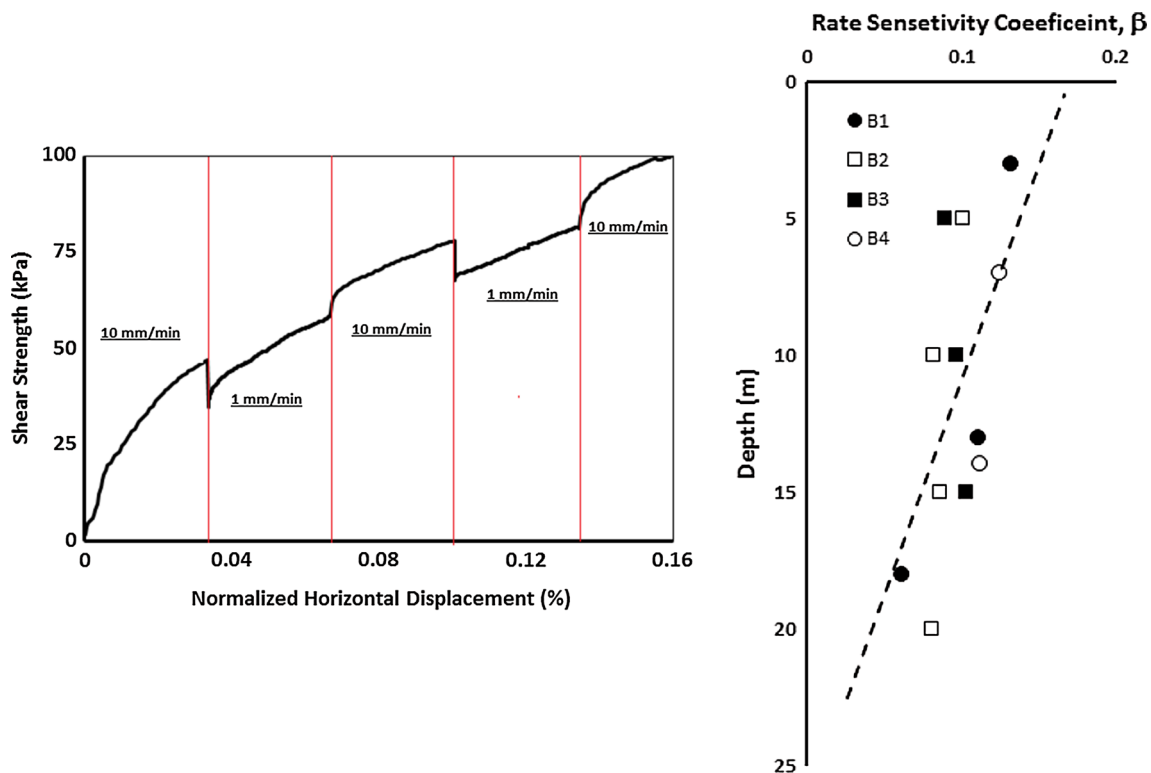

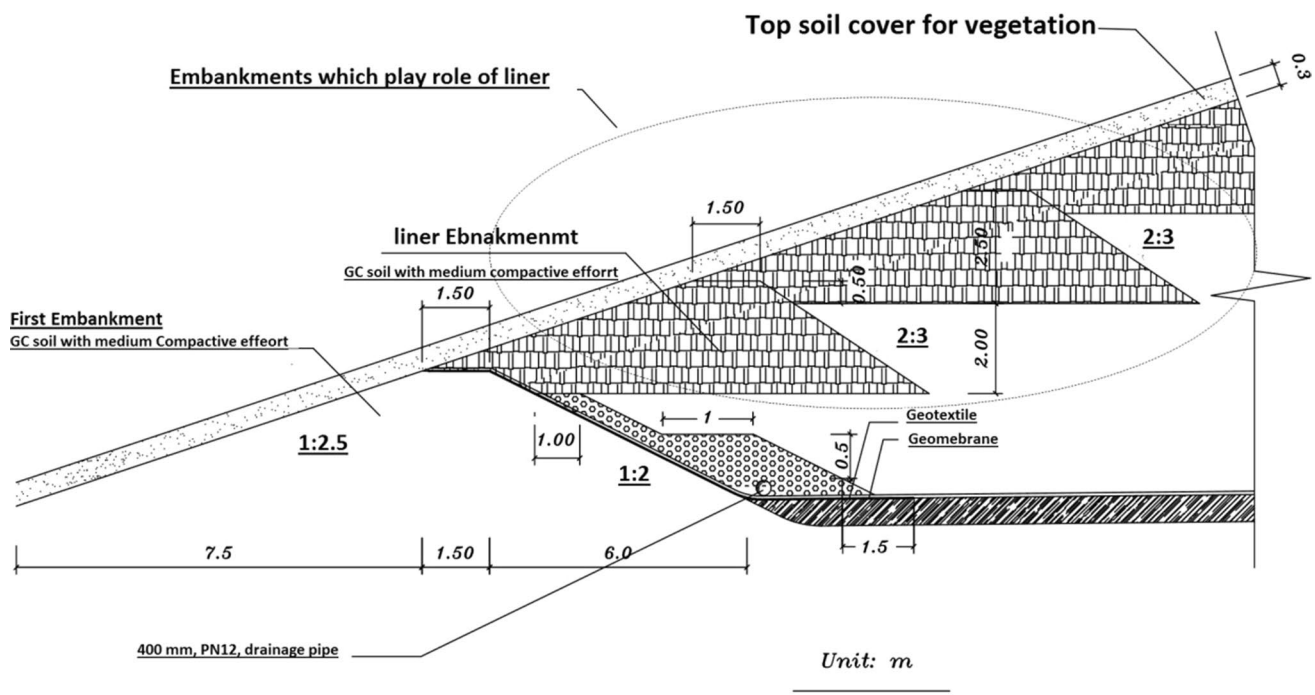**Fig. 18** Rate sensitivity of MSW in Saravan

Fig. 19 Details of the side slope cover

Construction program

The main aim of the rehabilitation project in Saravan was the construction of cover and liners on top of the dumpsite and side slopes to reduce the leachate production. To reach this aim, an evaluation on the geotechnical properties of MSW materials in the Saravan dumpsite was necessary by performing stability analyses on the side slopes, and achieving a minimum safety factor.

Figure 19 shows details of the side slope cover. It was concluded that the most proper soil to construct the required cover, embankments, is "GC" soils which are also common in construction of the core in the earth dams due to their low permeability and high shear strength of gravelly skeleton.

The construction of the first embankment includes the use of a geomembrane as well as geotextile and a drainage system consisting of a 400 mm, PN12, pipe and a filter of granular soils.

After the construction of the first embankment, it was backfilled with compacted aged waste, and the second embankment was constructed on top of the first embankment. The procedure was repeated to the top of the dumpsite. The final cover outer side has a 1:2.5 slope, while the first embankment inner side and all the other embankments have 1:2 and 2:3 slopes, respectively.

The PLAXIS 2D analyses showed that the modified form of side slopes with cover embankments meets the minimum factor of safety requirement of 1.5 under static condition.

Figure 20 shows the construction stage of side cover in the Saravan dumpsite. In Fig. 20a, the construction of the first embankment, installing the geomembrane and geotextile and the drainage pipe, is illustrated. In Fig. 20b, backfilling of the first embankment with MSW is depicted.

In Fig. 20c, it can be observed how the side embankment covers have shaped the side slopes of the Saravan dumpsite and finally in Fig. 20d, cutting the waste for modification of the geometry of side slope and the construction of embankments can be seen.

Conclusion

The Saravan dumpsite is the largest center for the disposal of solid waste in Rasht, capital of Guilan province, Iran. Despite accepting 700 tons of MSW per day, the Saravan dumpsite does not meet the requirements of a sanitary landfill. Lack of soil cover and of leachate and gas collection systems has led to multiple problems including bad odors at the region, and the discharge of a considerable amount of leachate to rivers and creeks at the downstream. Leachate, as a highly hazardous material, is required to be collected and treated. However, decreasing the production of leachate in landfills could decrease the cost of collection and treating, effectively.

Construction of soil covers at the top and side slopes of the dumpsite as an effective solution was considered. To

Fig. 20 Construction stage of side embankment covers

design and perform these soil covers, the geometry of the MSW slopes should first be modified which makes the geotechnical evaluation of MSW at the Saravan dumpsite, necessary. Geotechnical laboratory tests on MSW samples collected from different boreholes and depths were performed to evaluate the properties of MSW in this dumpsite.

Results showed that by increasing the retrieval depth, MSW samples become finer, with smaller fraction of soil-like material and lower organic and moisture content as a result of the advancement of waste decomposition.

Increasing the foil-like parts, with depth, caused a reduction in shear strength of MSW samples, as in direct shear test, the applied shearing planes are parallel to the fiber alignment.

In addition to the evaluation of shear strength by direct shear tests, performed back-analyses on unstable slopes in Saravan led to shear strength parameters comparable with laboratory test results.

Rate dependency evaluation of MSW showed that MSW materials in Saravan exhibit viscous behavior and are rate-sensitive. This rate sensitivity of MSW materials in Saravan probably causes a higher level of safety factor during dynamic loading compared to the static condition.

Finally, based on the shear strength parameters achieved, side slopes were geometrically modified to the slope of 1:2.5 with minimum requirements of the safety factor, 1.5.

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