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Shear strength characterization of municipal solid waste at the Suzhou landfill, China

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Abstract

The current practice of slope stability analysis for a municipal solid waste (MSW) landfill usually overlooks the dependence of waste properties on the fill age or embedment depth. Changes in shear strength of MSW as a function of fill age were investigated by performing field and laboratory studies on the Suzhou landfill in China. The field study included sampling from five boreholes advanced to the bottom of the landfill, cone penetration tests and monitoring of pore fluid pressures. Twenty-six borehole samples representative of different fill ages (0 to 13 years) were used to perform drained triaxial compression tests. The field and laboratory study showed that the waste body in the landfill can be sub-divided into several strata corresponding to different ranges of fill age. Each of the waste strata has individual composition and shear strength characteristics. The triaxial test results showed that the MSW samples exhibited a strain-hardening and contractive behavior. As the fill age of the waste increased from 1.7 years to 11 years, the cohesion mobilized at a strain level of 10% was found to decrease from 23.3 kPa to 0 kPa, and the mobilized friction angle at the same strain level increasing from 9.9° to 26°. For a confinement stress level greater than 50 kPa, the shear strength of the recently-placed MSW seemed to be lower than that of the older MSW. This behavior was consistent with the cone penetration test results. The field measurement of pore pressures revealed a perched leachate mound above an intermediate cover of soils and a substantial leachate mound near the bottom of the landfill. The measurements of shear strength properties and pore pressures were utilized to assess the slope stability of the Suzhou landfill.

Keywords: Municipal solid waste; Shear strength; Fill age; Cone penetration test; Leachate level; Slope stability

1. Introduction

Significant growth in population and economy has occurred in most cities of China since the 1990s. This growth has resulted in a rapid increase in the quantity of municipal solid waste (MSW). At present the per-capita generation of MSW in China has reached about 1 kg/day, and the annual total generation is approximately 150 million tons. About 90% of the huge amount of MSW is disposed of in landfills. Most of the landfills in major cities were built in the early of 1990 and now have reached the design service life. The expansion of the existing landfills is presently being undertaken in many cities of China due to the social and political problems associated with identifying new landfill sites.

The stability of waste mass is one of the major concerns associated with the design of landfill expansion in China. Past experience has shown that both vertical and lateral expansion of landfills can trigger waste mass instability. Vertical expansion generally involves a significant increase in landfill slope height. For example, the postponed closure of the Payatas landfill in Philippines eventually caused a flow slide in 2000, which killed at least 278 persons (Kavazanjian and Merry, 2005). Lateral expansion may involve a large excavation adjacent to the side slopes of the existing landfill. The largest waste mass instability in the United States occurred in 1996 following lateral expansion of an existing landfill (Eid et al., 2000). Another potential failure mechanism associated with the landfill expansion in China is slippage alone the weak interface associated with the intermediate liner system sandwiched between the existing and expanded waste masses. It should be noted that most of the existing landfills in China were not lined with clay liner or

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HDPE geomembrane. According to new regulations (CJJ 17-2004), a composite liner system must be installed at the bottom of the expanded landfill.

Information on the shear strength of the MSW is required for the assessment of slope stability since failures usually occur entirely or at least partially within the waste material. Numerous data on the shear strength of MSW have been obtained from both experimental measurements and back-analysis of field case histories over the last two decades (Landva and Clark, 1990; Singh and Murphy, 1990; Jessberger and Kockel, 1993; Kavazanjian et al., 1995; Gabr and Valero, 1995; Grisolia and Napoleoni, 1996; GeoSyntec, 1996; Manassero et al., 1996; Jones et al., 1997; Van Impe and Bouazza, 1998; Machado et al., 2002). However, the shear strength values reported in the literatures vary widely, with internal friction angle varying from 10° to 53° and cohesion varying from 0 to 67 kPa (Machado et al., 2002). The selection of appropriate shear strength parameters remains a challenging engineering design issue for a site-specific landfill. Variability in the shear strength parameters is due to the variableness of MSW compositions, the strain level at failure, the choice of representative samples and testing methods. An additional factor affecting shear strength is the change in shear strength with the fill age of waste because of the biodegradation of the organic component (Dixon and Jones, 2005). As far as the authors are aware, little experimental data are available to evaluate the aging effect.

Information on the leachate mound in a landfill is also required to evaluate the waste mass stability. This information is particularly important for landfills located in humid regions (e.g., in the south-east of China). Most of the existing landfills in China do not have effective facilities for rainwater interception and leachate drainage. Field reconnaissance has indicated that the leachate mound in landfills is quite high and leachate exits on the slope surface during the wet season. However, few field investigations have been carried out on this aspect.

This paper presents a field and laboratory study on the Suzhou landfill in China. The field study included drilling five boreholes, obtaining samples of MSW, driving cone penetration tests and monitoring of pore pressures. Borehole samples of the MSW were taken from various depths and taken to the laboratory for the determination of waste composition, volume-mass properties and shear strength properties. The waste strata within the landfill were dated to the fill age of waste. The changes in compositions and shear strength properties with the fill age were identified. The hydrogeological conditions of the landfill were discussed on the basis of the pore pressure measurements in the field. The cone penetration test results were interpreted on the basis of the measurements of shear strength properties and pore pressures. The stability of the existing landfill was also investigated by taking into account the variation in shear strength properties with depth and the height of leachate mound.

2. Landfill site and scheme of field study

The Suzhou landfill was put into operation in 1993. The landfill is located in a valley surrounded by hills about 13 km to the south of Suzhou city. The landfill was designed to contain 4.7 million m^3 municipal solid wastes and serve for about 15 years. At present, the landfill is receiving MSW at a rate of about 1600 tons/day. Fig. 1 shows the main cross-section of the landfill as of April 2006, when the field investigation was carried out. The landfill consists of a number of filled platforms that are set back at an embankment slope of 3H/1V. A rock-fill dam retains the lowest platform. It is anticipated that the landfill will reach its top design level (i.e., +80 m Ordnance Datum) by the end of 2008. Vertical and lateral expansion of the existing landfill is under design. The preliminary design involves expanding the existing landfill from a level of 80 m to 120 m in the vertical direction, and 400 m outward from the present landfill boundaries in the horizontal direction.

As shown in Fig. 1, the bottom of the existing landfill was not lined with any form of engineered barrier. An injected grout curtain was installed under the retaining wall of the leachate pond to limit downstream movement of leachate. The natural soil strata below the landfill bottom was composed of a layer of alluvial-colluvium deposit of Quaternary, highly-decomposed sandstone along with slightly-decomposed and fresh sandstone (lower–middle Devonian). The alluvial-colluvium deposit was composed of gravelly clay with a thickness ranging from 5 to 27 m. The mean values of shear strength parameters (i.e., c' and ϕ') measured for the gravelly clay were approximately 5 kPa and 31°, respectively. The water permeability for the gravelly clay was measured using double-ring infiltration tests, and it ranged from

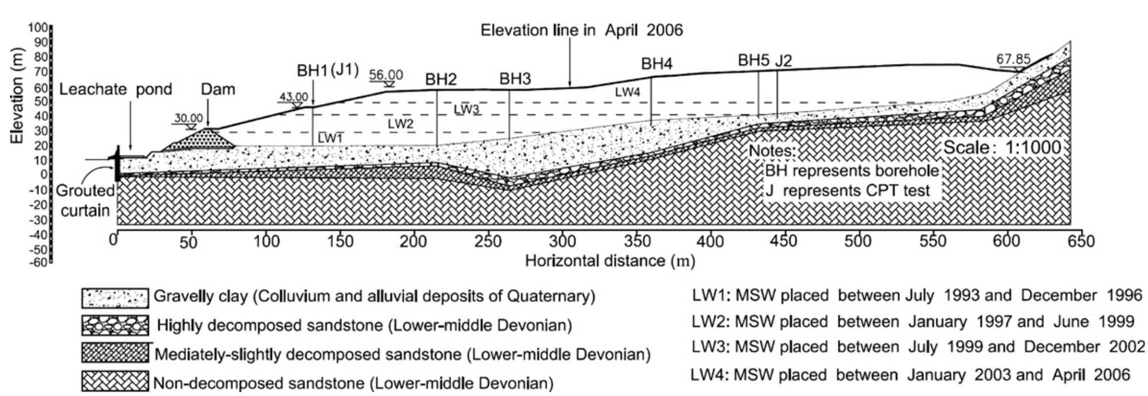

Fig. 1. Cross-section of the existing landfill in Suzhou of China and layout of boreholes and CPT locations.

1×10^{-6} m/s to 5×10^{-6} m/s. The decomposed sandstone below the gravelly clay had a high shear strength. Joints were well developed in the highly-decomposed sandstone, resulting in a high hydraulic conductivity. However, the fresh rock at the bottom had a high integrity and a water permeability less than 1×10^{-9} m/s. The grout curtain was made to extend to the underlying fresh rock. The grout curtain and the fresh rock were expected to constitute a closed barrier system against the leachate in the landfill. However, groundwater monitoring downstream of the grout curtain indicated that the barrier system was not perfect. In accordance with the new regulation, the bottom of the expanded waste body will be lined with a composite liner system.

A field study was carried out on the existing landfill to assess the safety of the existing and expanded waste body. The field study consisted of borehole investigations, sampling of the waste materials, cone penetration tests and monitoring of pore fluid pressures. Five boreholes (BH1 to BH5) were drilled to the bottom of the existing landfill (see Fig. 1). The depths of the boreholes ranged from 25 to 38 m. The boreholes were drilled without an introduction of drilling mud and liquids. To avoid the collapse of the borehole wall, a system of steel casings were installed in each borehole. Each borehole consisted of three vertical sections (i.e., from top to a depth of 10 m, from 10 m to 20 m and below 20 m) with different-diameter casings installed. The borehole diameters for the three sections were 130 mm, 110 mm and 90 mm, respectively. MSW samples were taken using heavy-wall samplers at an interval of 1 or 2 m. More than 20 samples were obtained from each of the boreholes. The sample diameters were about 96 mm for samples taken from above a depth of 20 m and 82 mm for samples taken from below a depth of 20 m. Each sample was about 200 mm in length.

Two cone penetration tests (i.e., J1 and J2) were conducted near boreholes BH1 and BH5. The cone penetration testing apparatus was a conventional electrical cone with a 43.7 mm diameter cone-shaped tip with an apex angle of 60° (i.e., nominal

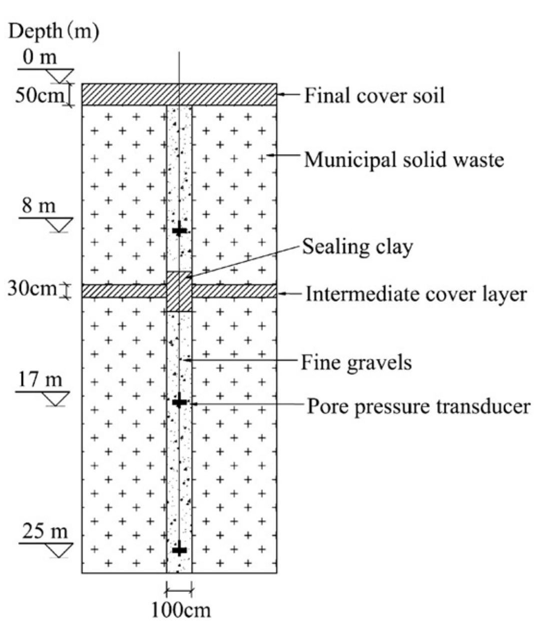

Fig. 2. Layout of pore pressure transducers in boreholes BH1 and BH3.

base area of 1000 mm^2) and a 43.7 mm × 109.3 mm long cylindrical sleeve (i.e., nominal area of 1.5×10^4 mm^2). The rate of penetration was controlled at 1 m/min. Cone resistance and side friction resistance were recorded at intervals of 50 mm.

After the completion of sampling, pore pressure transducers were installed in two boreholes (i.e., BH1 and BH3) to measure pore fluid pressures in the landfill. Fig. 2 shows a layout of pore pressure transducers. In each borehole, there were three transducers located at depths of 8 m, 17 m and 25 m. The boreholes were backfilled with gravel (3 to 6 mm in grain size) with the exception of the top 1 m and the section corresponding to the intermediate cover soil layer at a depth of about 10 m. The cover soil layer was identified as being relatively impermeable from the borehole log. These two exceptions were backfilled with a sealing clay for a length of 1 m. It was expected that the two transducers separated by the sealing layer could register the leachate heads within different hydrogeological regimes.

3. Laboratory testing method

3.1. Determination of waste composition and volume-mass properties

Each borehole sample taken from the landfill was used to determine the basic physical properties including composition of MSW, unit weight, overall specific gravity, water content and void ratio. In addition, samples were also to be used as part of the triaxial testing program. The following procedures were adopted in handling each of the samples used for triaxial tests. Firstly, the weight and dimensions (i.e., diameter and height) of the sample were measured for the determination of the bulk density. Secondly, the whole borehole sample was installed in a triaxial cell to perform a triaxial compression test. Thirdly, after the competition of the triaxial test, all the material was retrieved from the triaxial cell, and then dried at an oven with a temperature of 60 °C. The water content of each sample was then calculated. Fourthly, the major components of the sample (i.e., plastic, paste, textiles, wood, metal, glass, ceramic etc.) were identified using an optical investigation and individually weighted. Finally, all the material was divided into two parts, each having a similar weight and composition. For the first portion, all the materials except the plastic matter were incinerated for 2 h in an oven with a temperature of 300 °C. This allowed the organic content to be determined by weighting the amount of incineration loss. For the second portion, all the materials were placed in a cylindrical container with a siphon tube. The overall specific gravity of each sample was measured by using a water replacement method. The void ratio of the sample was calculated from the measurements of the overall specific gravity and dry density.

3.2. Triaxial compression tests

The whole of the borehole samples with a diameter of approximately 82 mm or 96 mm and a height of 200 mm were used as the specimens for the triaxial compression tests. No trimming, or a minor amount of trimming, was used on each of

Table 1
Laboratory test specimen information

Sub-layer no./ fill age	Test group no.	Specimen ID	Embedding depth (m)	Specimen diameter (mm)	σ_3' (kPa)	e_0
LW1/9.3–12.8 years	1	BH1-20	20.4	78.3	100	1.88
		BH1-21	24.9	78.8	200	2.02
		BH5-13	23.1	79.9	400	1.93
LW2/6.8–9.3 years	2	BH1-9	7.6	92.0	50	1.82
		BH1-11	11.4	94.7	100	2.12
		BH1-13	13.4	91.2	400	1.65
		BH1-16	16.4	94.0	200	1.39
	3	BH3-20	22.9	79.0	50	2.69
		BH3-21	24	80.5	100	3.37
		BH3-22	25	80.5	200	2.16
		BH5-13	23.1	79.9	400	1.93
	4	BH5-11	19.9	77.8	200	1.24
		BH5-16	28.1	79.0	400	1.34
		BH5-17	29.1	79.5	50	2.25
LW3/3.3–6.8 years	5	BH1-1	1.3	94.1	50	1.45
		BH1-3	3.8	93.9	200	1.83
		BH1-5	5.6	98.1	100	1.88
		BH1-13	13.4	91.2	400	1.65
	6	BH3-7	8.4	94.6	100	1.66
		BH3-8	10.4	85.0	200	1.60
		BH3-9	11.4	92.9	400	1.62
LW4/0–3.3 years	7	BH2-1	1.7	94.1	100	1.91
		BH2-3	5.7	95.0	50	1.57
		BH3-1	1.7	93.7	400	3.72
		BH3-3	4.8	95.0	200	3.64
	8	BH4-1	0.7	90.3	50	5.78
		BH4-4	3.7	87.0	400	2.33
		BH4-5	4.7	92.3	200	3.76

Notes: σ_3': effective confining pressure for the triaxial tests; e_0: initial void ratio of specimen prior to consolidation.

the specimens to avoid disturbance of the waste structure. Here it needs to be acknowledged that there must be some disturbance to the samples during the borehole sampling. There were in total 26 effective specimens tested that were classified into 8 groups corresponding to different ranges in fill age. The description for each of the samples is listed in Table 1.

Two conventional triaxial apparatus accommodating specimens with a diameter up to 100 mm were modified for the laboratory study. The length of the loading ram was extended to allow for a large axial strain associated with the testing of the MSW. The volume change gauge was also modified to accommodate large volume changes. Consolidated drained compression tests (CD) with a control of strain rate were adopted for testing each of the samples. After assembly of each MSW specimen, saturation was achieved by percolating de-air water through the specimen. Further saturation was accomplished through the application of a backpressure ranging from 100 to 200 kPa. It was assumed that the saturation process would not significantly alter the mechanical properties since the initial state of the wastes was relatively wet. The specimens in each group were consolidated to effective confining pressures of 50, 100, 200 and 400 kPa. Puncturing of the membranes by a sharp matter in the specimen occurred to several specimens when the effective cell pressure was higher than 200 kPa. Once this took place, another specimen with a similar fill age was used to repeat the test. The strain rate for the drained shearing tests was set as 0.3 mm/min. The strain rate was estimated by the equation proposed by Bishop and Henkel (1962), in which the coefficient of consolidation (c_v) was adopted as 5.6×10^{-6} m^2/s. Each specimen was sheared to a strain level beyond 20%.

4. Characterization of waste strata and shear strength

4.1. Waste strata

Fig. 3 shows an array of disturbed samples taken at various depths from borehole BH4. The embedment depth of the samples increases from top to bottom and left to right in the figure. For the shallow depths (i.e., within upper 10 m), the MSW sample is quite heterogeneous and has variable particle sizes. As the embedment depth increases, the samples contain a higher cinder content and become more uniform. As the waste material was piled up layer by layer in the landfill (i.e., approximately 5 m of initial thickness for each layer), the embedment depth of the waste could be correlated with the fill age. On the basis of the borehole logs and the record of landfill operation, a correlation could be made between the fill age and depth. As shown in Fig. 1, the landfill could be divided into four sub-layers corresponding to four different ranges of fill age (i.e., 0–3.3, 3.3–6.8, 6.8–9.3 and 9.3–12.8 years from top to bottom). The range of fill age for each MSW sample could be identified and is shown in Table 1.

An intermediate soil cover layer was found in each of the five boreholes. The cover layer was located at a depth of about 10 m into the borehole with the exception of borehole BH4 (i.e., located at a depth of 18 m). It should be noted that the intermediate soil cover layer was relatively impermeable as compared with the MSW. The intermediate soil cover layer makes the hydrogeological system in the landfill more complex. This will be further discussed later in this paper.

4.2. Change in composition of MSW with age

Information on the waste composition is of assistance in characterizing the waste strata as well as evaluating the engineering properties of the waste. The collected MSW generally

Fig. 3. Disturbed MSW samples taken at different depths (i.e., embedment depth increases from left to right).

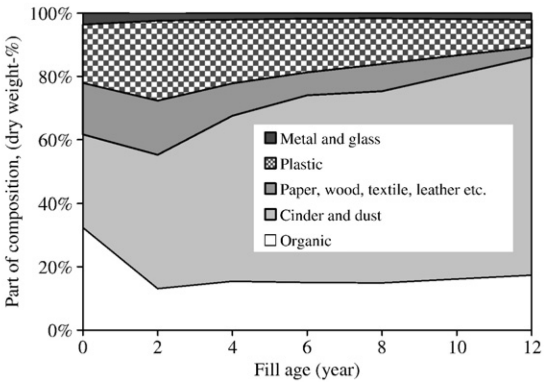

Fig. 4. Variations in the MSW composition with fill age.

consists of putrescent organics (i.e., food and garden wastes), cinder, dust, paper, plastics, rubber, textiles, wood, glass, metal etc. After being placed in landfills, waste composition inevitably changes with time due to biological degradation of the organics. Fig. 4 shows the changes in MSW composition with the fill age. The waste composition was known from the composition analysis conducted on the samples from each borehole. The fraction of each component was measured and calculated using a dry-weight basis. The initial data point (i.e., at zero year) in Fig. 4 was determined from the composition of the fresh MSW generated in 2006. After the MSW was disposed in the landfill, its organic content decreased significantly with time during the first two years. Then the organic content remained at a value of approximately 18%. The decrease in organic content is related to the fast degradation of the putrescent organics. At the same time a significant increase in the cinder content was observed with the fill age. The MSW with a fill age greater than 6 years usually consisted of over 50% cinder content. It is generally believed that the daily covers of soils placed during the landfill operation also contributed to the increase in cinder content. Both the fiber content (i.e., including textiles, wood, paper, leather, etc.) and the plastic content exhibit a decreasing trend with the fill age. It should be noted that the decreasing trend is partially attributed to the change of MSW composition generated over the last decade. The total fraction of fiber and plastic ranged from 15 to 40%, depending on the age of the fill. The fiber-like materials and the plastic materials are known to act as a reinforcement during triaxial shearing, resulting in a strain-hardening behavior of MSW (Machado et al., 2002).

4.3. Variation of dry density with depth

The density of the MSW is an important parameter for calculating self-weight stresses in a landfill. These stresses are required for both stability and deformation analyses of landfill. Fig. 5 shows variations in dry density with the embedment depth for the samples taken from the five boreholes (i.e., BH1 to BH5). Almost all the data points fall into the range from 0.3 to 1.2 Mg/m^3. A trend line was plotted to fit the data points obtained from boreholes BH2 and BH3, in which there is a similar distribution of waste strata along the depth. There appears to be a general increase in dry density with the embedment depth. The increase of dry density is primarily attributable to an increase in the effective overburden pressure with depth. There may also be a change in the waste composition with the fill age (see Fig. 4). The scatter of the data points around the trend line is understandable by considering the heterogeneous nature of MSW. Of course, the discrepancy may partially be due to disturbance and localization effects associated with the borehole sampling. Regardless of this, the measurements of dry density are comparable to the data reported by Zekkos et al. (2006).

4.4. Shear strength characteristics of the MSW

A total of 8 groups of consolidated drained triaxial compression tests were carried out to investigate the shear strength characteristics of the MSW samples. One group of representative stress–strain test results is shown in Fig. 6. The four stress–strain curves correspond to confining pressures of 50, 100, 200 and 400 kPa. The results were obtained from four samples with age ranging from 6.8 to 9.3 years (see Table 1). As shown in Fig. 6(a), the stress–strain curves exhibited a typical strain-hardening behavior of MSW. The deviator stress of each stress–strain curve increased continuously with axial strain without reaching an asymptotic value. It appears that the rate of stress increase is greater when the axial strain exceeds a value of 20%, particularly at high confining pressures. This may indicate that the reinforcing effect contributed by the fibrous materials becomes pronounced at a high strain level and under a high confining pressure. The volumetric strain versus axial strain curves shown in Fig. 6(b) demonstrate that all the specimens exhibited a contractive behavior during shearing. The volumetric strains measured at the end of test all exceeded 10%. The

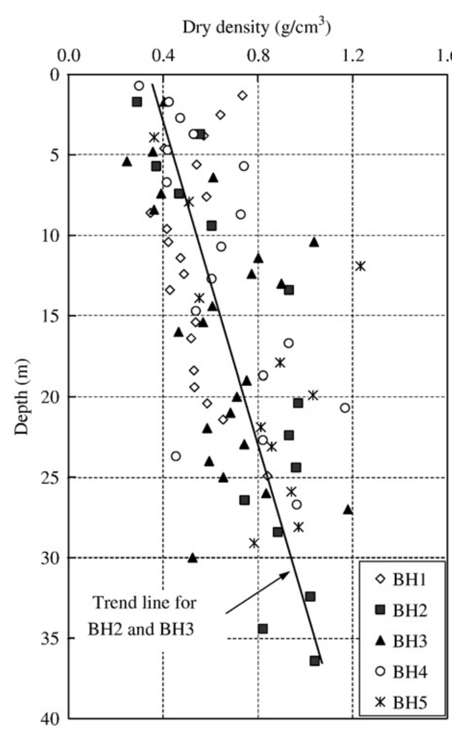

Fig. 5. Variations in dry density with the embedment depth.

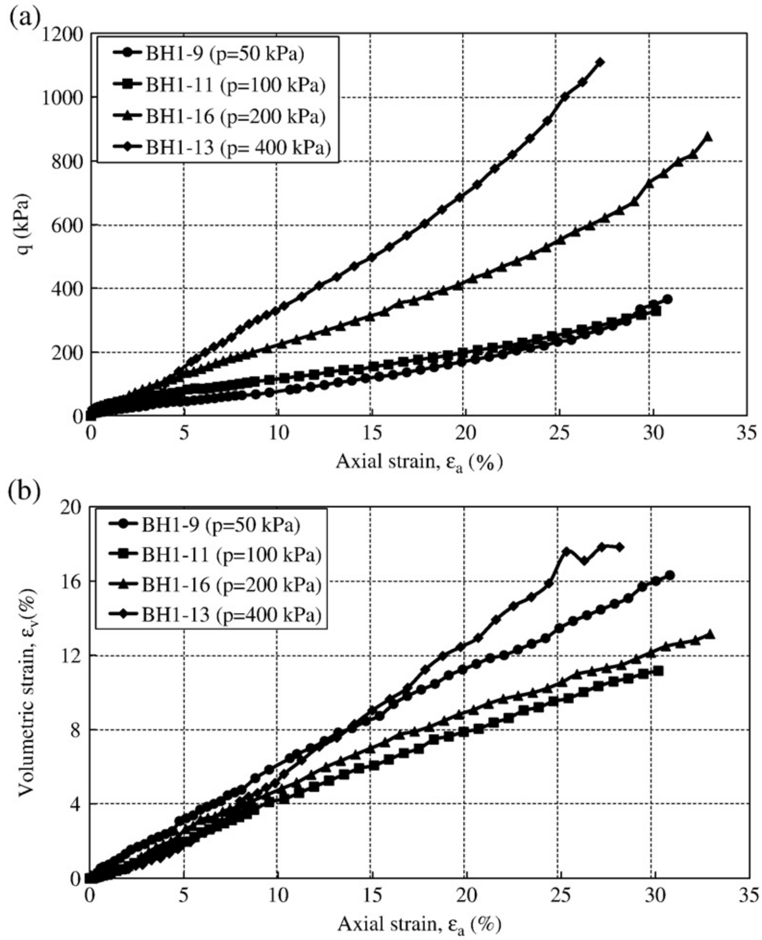

Fig. 6. Stress–strain relationships obtained from four samples with a fill age between 6.8 and 9.3 years: (a) q–ε_a ; (b) ε_v–ε_a.

above stress–strain behavior of MSW is generally consistent with that observed by other researchers (Grisolia et al., 1996; Jessberger and Kockel, 1993; Machado et al., 2002).

The MSW exhibited a strain-hardening behavior during triaxial shearing. Therefore, it would be appropriate to define strength in terms of the mobilized shear strength corresponding to a selected strain level. The shear strength mobilized at three strain levels (i.e., 5%, 10% and 20%) was investigated. Fig. 7 (a), (b), (c) and (d) shows the mobilized shear strengths measured from the MSW samples corresponding to four different ranges of fill age (i.e., 0–3.3, 3.3–6.8, 6.8–9.3 and 9.3–12.8 years). In each case, three shear strength envelopes could be drawn corresponding to strain levels of 5%, 10% and 20%. Best-fitting of the data points was then undertaken corresponding to each selected strain level. With the exception of Fig. 7(d), each of the shear strength envelopes represents the average of data from two or three groups of triaxial tests. Although there is some discrepancy evident between two or three of the groups, a linear relationship exists between the mobilized shear stress and the mean stress for each strain level. Shear strength parameters can be obtained in terms of the mobilized cohesion, c', and mobilized angle of internal friction, ϕ'. By comparing the shear strength envelopes for different ranges of fill age, it can be seen that the mobilized shear strength of the recent MSW is lower than that of the older MSW for a mean stress level greater than 50 kPa (i.e., $p' \geq 50$ kPa). This finding is consistent with the test results reported by Van Impe (1998).

Fig. 8 shows the relationships of mobilized shear strength parameters (i.e., c' and ϕ') to the fill age of waste. The values of fill age corresponding to the data points was taken as being equal to the middle values of the four ranges (i.e., 0–3.3, 3.3–6.8, 6.8–9.3 and 9.3–12.8 years). Both the mobilized cohesion and mobilized angle of internal friction increase with strain level as a result of the strain-hardening behavior. For a given strain level, it was found that the mobilized cohesion decreases with an increase in the fill age of waste, and the value of mobilized friction angle increases with the fill age. The trends for the three strain levels are consistent. As shown in Fig. 8, for the MSW with a fill age of about 11 years, the mobilized cohesion is close to zero and the mobilized angle of internal friction is up to 39°. For the recently-placed MSW, the mobilized cohesion and mobilized angle of internal friction corresponding to a strain level of 10% are 23 kPa and 10°, respectively.

The observed changes of shear strength with the fill age can be explained by considering the change in the MSW composition with age (see Fig. 4). The recently-placed MSW consisted of 25% plastic, 17% fiber, 16% organic and 40%

cinder. It should be noted that the composition percentages were obtained on a dry-weight basis. If a volume basis was used, the fraction of plastic and fiber materials would be predominant because of their low density. This indicates that the plastic and fiber materials will dominate on the shear plane of recently-placed MSW. The predominant plastic and fiber materials generally pose a low friction resistance, and hence lead to a low mobilized friction angle. On the other hand, the plastic and fiber materials provide a significant reinforcement effect, resulting in the relatively high mobilized cohesion for the recently-placed MSW. Here, it should be pointed out that the contribution of fibrous materials to shear strength depends on the preferential orientation of these components relative to the direction of shearing. The MSW with a fill age over 10 years consisted of 70% cinder, 16% organic, 9% plastic and 3% fiber. The cinder content dominated the material and resulted in a high mobilized angle of internal friction and a low mobilized cohesion.

It should be pointed out that the changes in the shear strength characteristic with the fill age shown in Fig. 8 were not fully attributable to the degradation process of the waste when the fill age is located in between 5 and 12 years. This is because the composition of the original waste (i.e., when collected in a fresh state) has changed in the city over the period from 1993 to 2001 (Chen and Zhan, 2006). However, the data points located between 0 and 5 years basically reflect the influence of waste degradation (i.e., aging) since the original waste collected from 2001 to 2006 has essentially maintained the same composition (Chen and Zhan, 2006). It would appear that the influence of degradation on the mobilized angle of internal friction is more significant than the effect on the mobilized cohesion. The significant increase in the angle of internal friction with age is likely related to the rapid degradation of the food and garden wastes, which occupy about 50% on a wet-weight basis. The insignificant change of cohesion is likely related to the slow degradation of the reinforcing components (i.e., plastic, textile, wood, leather, etc.). The above discussion indicates that correlating the shear strength characteristics of the MSW to its fill age is a complex task. An alternative approach would be to correlate the properties to the waste classification with regard to the component type, size, shape and degradability. The classification system developed by Dixon and Langer (2006) has provided an appropriate basis for such an alternative approach. In addition, the influence of waste fabric (e.g., preferential orientation of fibrous materials) on shear strength characteristic should be further investigated.

Fig. 9 shows a plot of mobilized cohesion, c', versus mobilized angle of internal friction, ϕ', for the experimental data obtained from this study. Several experimental data are

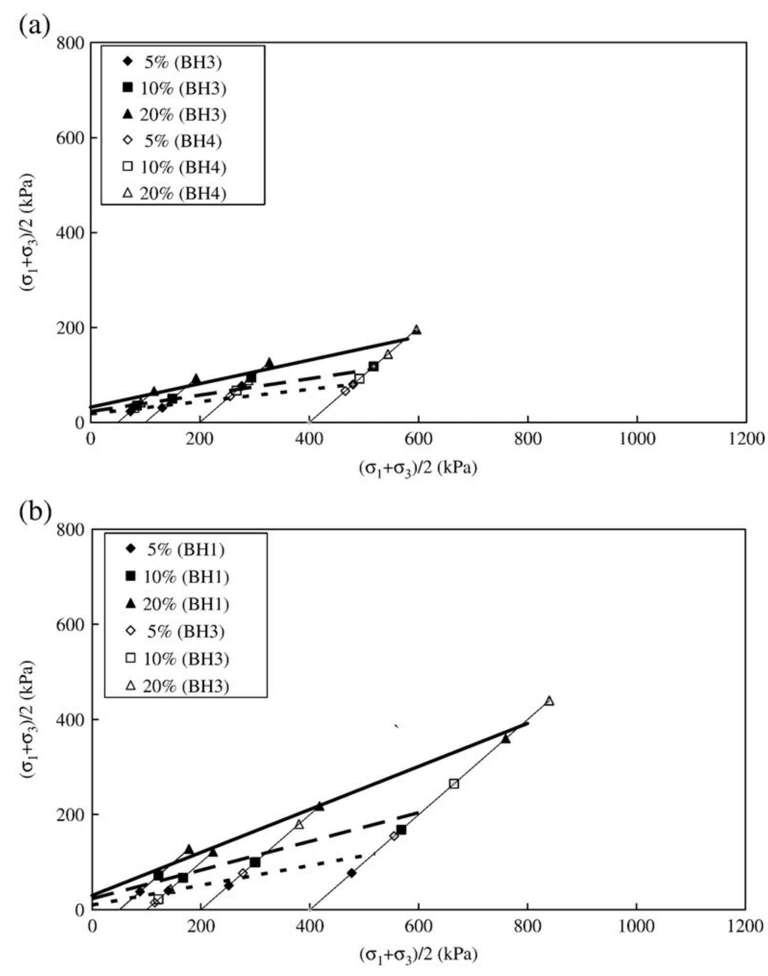

Fig. 7. Shear strength envelopes obtained from the samples with a fill age between: (a) 0–3.3 years; (b) 3.5–6.8 years; (c) 6.8–9.3 years; (d) 9.3–12.8 years.

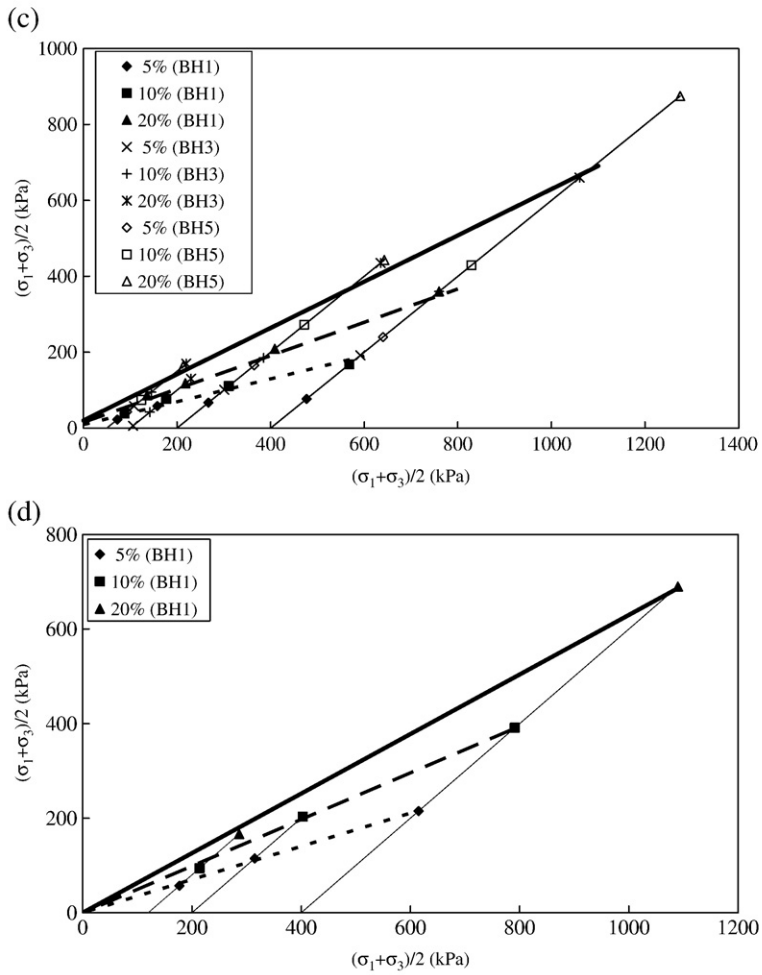

Fig. 7 (*continued*).

included from five published research papers. It should be noted that only data obtained from tests on relatively large-size specimens are presented in Fig. 9 (see Table 2). The data sets from this study can be separated into two groups with one loci tending in a radial direction and the other tending in an annular direction. Each of the radial loci passes through data points corresponding to a same fill age (i.e., a synchronous locus). The synchronous loci sub-divide the rectangular coordinates into different zones corresponding to different ranges of fill age. The shear strength properties obtained from tests on the recent MSW are located in the left-upper zone with a high mobilized cohesion and a low mobilized angle of internal friction, and vice

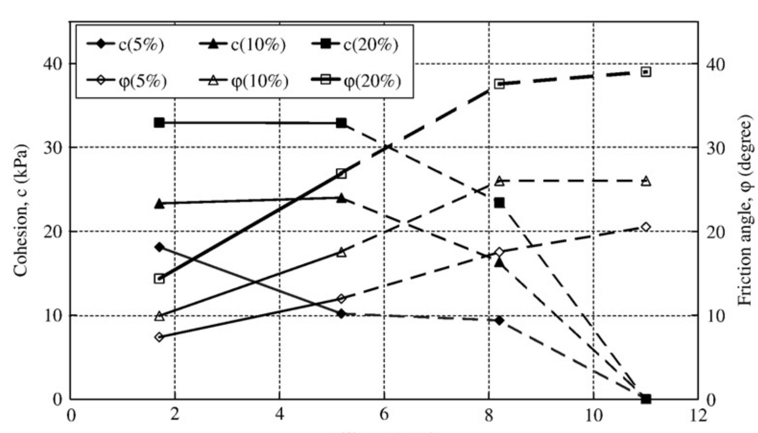

Fig. 8. Relationships of mobilized shear strength parameters at a range of strains to the fill age of MSW (notes: the data points connected by the dashed lines were obtained from samples with different original waste compositions).

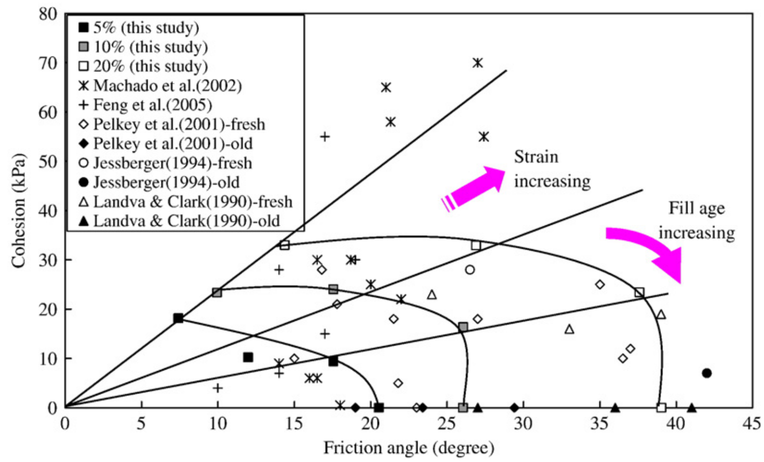

Fig. 9. Summary of mobilized shear strength parameters reported in the research literatures.

versa. Each of the annular loci passes through the data points corresponding to the same strain level (i.e., an iso-strain locus). The iso-strain loci sub-divide the rectangular coordinates into different zones corresponding to different levels of strain. As the strain level increases, both the mobilized cohesion and mobilized angle of internal friction increase, and hence the iso-strain loci expand outwards. The above chart consisting of synchronous and iso-strain loci can be used to interpret the experimental data from the five other research papers listed in Table 2. It is found that most of the data points fit reasonably to the above chart. The chart provides a useful reference for the interpretation of MSW shear strength data in the literature. Of course, more data and information are needed to improve the shear strength chart.

5. Characterization of leachate mound in the landfill

5.1. Hydrogeology system in the landfill

The height of leachate mound in the landfill has an important influence on the overall stability of the landfill. This is particularly true when considering the relatively low dry density of the waste material (see Fig. 5). The height of leachate mount in a landfill is related to the water balance in the hydrogeological system. Fig. 10 shows a schematic diagram of water balance in the Suzhou landfill. The input of water to the landfill includes rainfall infiltration on the surface of the landfill, leachate generation caused by degradation and consolidation of waste, as well as surface and sub-surface inflow from the upstream catchment zone. The output of water from the landfill mainly includes the actual evaporation from the surface of the landfill, and leachate discharge from the toe drain constructed near the bottom of the rock-fill dam as well as leachate discharge through the bottom of the landfill. The Suzhou landfill is located in a humid region with an annual precipitation of about 1100 mm. The landfill has been operated with no cover for most of the existence of the landfill. The interception trench constructed around the landfill was found to be ineffective in stopping the sub-surface inflow from the upstream catchment area. In addition, a gradual clogging was observed on the toe drain near the bottom of the rock-fill dam. The above conditions have resulted in a continual accumulation of water, and hence caused a leachate mound in the landfill. Leachate was found to exit on the sloping surface of the landfill during a wet season.

5.2. Variation in water content of waste with depth

The distribution of water (or leachate) inside the landfill is anticipated to form quite a complex pattern due to the heterogeneous nature of the waste material. Fig. 11 shows the variation of water content with the depth measured in the five boreholes (i.e., BH1 to BH5). A full saturation line was also plotted in the figure for a reference purpose. The full saturation line was calculated from the best-fit profiles of dry density and void ratio. A general trend of decreasing water content with depth was observed. The trend corresponded with the increase in the dry density of the MSW with depth. It was observed that most of the data points at the lower part (about 8 to 10 m in length) are close to the full saturation line. The data indicates that the waste fill in the lower part of the landfill are in a saturated or nearly saturated state. This will be further discussed on the base of the measurement of pore pressures.

5.3. Pore pressures

Fig. 12 shows the changes of pore pressure with depth as recorded by the transducers installed in boreholes BH1 and BH3. The pore pressures represent the total pressures resulting from gas and leachate. The top levels of leachate observed while drilling the two boreholes were also shown in the figure to provide a reference. The transducers in borehole BH1 registered pore pressures of 50, 80 and 145 kPa at depths of 8, 17 and 24.5 m, respectively. The pore pressures measured in borehole BH3 were obviously lower than those obtained from borehole BH1 for all the three depths, regardless of the higher leachate surface observed while drilling. It should be recalled that the bottom of the landfill is sloping and borehole BH1 is located downstream of borehole BH3 (see Fig. 1). Between the depths

Table 2
List of literatures report shear strength parameters

Reference	Test type	Specimen information			Strain (%)/ displacement (mm)	Strength parameters	
		Composition/producing area	Age (year)	Size (cm)		c (kPa)	φ (°)
Machado et al. (2002)	Triaxial test	Cinder 55%, stone 10%, plastic 17%, wood 4%, paper 2%, textile 3%, metal 5%, glass 2%, rubber 2%	15 years	20×40	5%	9	14
				15×30		6	16.5
				20×40		6	16
				15×30		0.5	18
				20×40	10%	30	16.5
				15×30		30	18.7
				20×40		25	20
				15×30		22	22
				20×40	20%	65	21
				15×30		58	21.3
				20×40		70	27
				15×30		55	27.4
Feng (2005)	Triaxial test	Cinder 57%, organics 17%, plastic 7%, wood 5%, paper 4%, textile 8%, metal 1%, glass 1%	5 years	30×60	5%	4	10
						7	14
					10%	28	14
						15	17
					15%	55	17
						30	19
Pelkey et al. (2001)	Large direct shear	Typical MSW/Blackfoot*	Fresh	30×45	25	21	17.8
					>90 (peak)	25	35
		Shredded MSW/Edmonton*			25	5	21.8
					>60 (peak)	18	27
		Wood waste/Edmundston*			25	0	23
					>160 (peak)	10	36.5
		Typical MSW/Hantsport NS*			25	12	37
					>200 (peak)	10	15
		Artificial MSW/UNB			25	28	16.8
					>35 (peak)	18	21.5
	Large simple shear	Artificial MSW/UNB*	8 years	30×45	10%	0	19
					20%	0	23.4
					>40% (peak)	0	29.4
Jessberger (1994)	Simple shear	NA	0.8 years	NA	NA	7	42
		NA	Fresh	NA	NA	28	26.5
Landva and Clark (1990)	Large direct shear	Shredded MSW/Edmonton*	Fresh	NA	NA	23	24
		Typical MSW/Blackfoot*	Fresh	NA	NA	19	39
					NA	16	33
		Artificial refuse/UNB*	8 years	NA	NA	0	27
					NA	0	41
		Typical MSW/Hantsport	Old	NA	NA	0	36

Notes: (1) *: *Blackfoot* — high amount of wood waste with some plastics, soils, glass etc.; *Edmonton* — high amount of plastic and textiles, paper, wood waste, metal, glass, gravel etc.; *Edmundston* — high amount of wood waste, some cardboard and small amount of gravel; *Hantsport NS* — wood waste, plastic, metal wire, wool, glass and gravel; *UNB* — high percentage of fines, some paper, rubber and wood.
(2) NA — not available; peak — shear displacement at peak shear stress.

of 8 m and 17 m the gradients of pore pressure for each of the boreholes (i.e., BH1 and BH3) were found to be significantly greater than the static hydraulic gradients. This indicates that the wastes within the region may be unsaturated and downward flow of leachate exists. The pore water pressure profiles also indicate that the leachate mound above a depth of 8 m is in a perched state. This finding is further supported by the relatively impermeable clayey soil layer observed at the depth during the drilling program. By taking the observed leachate surface in borehole BH1 as a reference, the pore pressure profile above a depth of 8 m was approximated (see the dashed line in Fig. 12). For the 8 m long section near the bottom of the landfill, the gradient of the pore pressure profile for each of the boreholes (i.e., BH1 and BH3) was found to be close to the static hydraulic gradient. This indicates that the MSW within the region was saturated or nearly saturated. In other words, there exists a saturated zone with a thickness of about 8 m just above the landfill bottom. The measured pore pressures at the lower part were basically consistent with the measurement of water content. The substantial leachate mound and high pore pressures in the landfill are a concern from a slope stability standpoint. The effect of leachate level on the slope stability is discussed later in this paper.

6. Cone penetration test results

It is of value to use *in situ* test methods to characterize the mechanical properties of MSW considering the difficulties

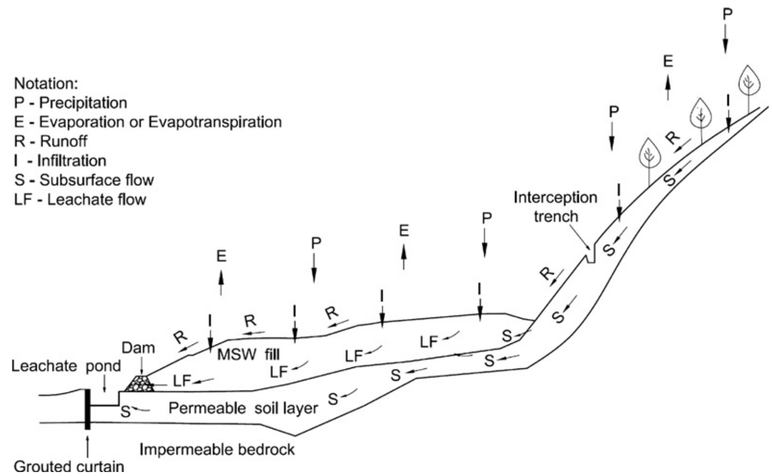

Fig. 10. A schematic diagram showing the hydrogeology system in the Suzhou landfill.

associated with recovery and testing of undisturbed samples. Kavazanjian (2003) provided a comprehensive review on evaluating MSW properties using field measurement. Kavazanjian et al. (1996) and Abbiss (2001) utilized surface wave techniques to measure shear wave velocity and damping ratio of MSW. Dixon et al. (2006) used pressuremeter tests to measure the *in situ* shear stiffness of MSW, and obtained valuable data. However, as far as the authors are aware, there are few cone penetration test results from landfills reported in the literature.

Fig. 13 shows the result from the cone penetration test (J1) conducted near borehole BH1, in which the MSW had fill ages ranging from 6 to 12.8 years. Both the tip resistance (q_c) and the sleeve resistance (f_s) fluctuate greatly with depth and there appears to be some abnormal data points with excessively high q_c values. The fluctuations are indicative of the highly heterogeneous and variable nature of MSW. The abnormal data points may result from the cone tip encountering a relatively large-sized, rigid material (e.g., stone, concrete block etc.). If the abnormal data points (i.e., $q_c > 8$ MPa or $f_s > 400$ kPa) are ignored, the values of tip resistance, q_c, against the municipal solid wastes generally varies from 1 to 8 MPa with the middle values mostly lying in between 2 and 4 MPa. The middle trend lines in Fig. 13 were plotted by taking average values every 1 m from the top surface. From the top surface to a depth of 20 m there is a general increase in q_c with increasing depth, in particular from 12 to 18 m. However, it was not anticipated that the values of q_c would not increase further below a depth of 20 m.

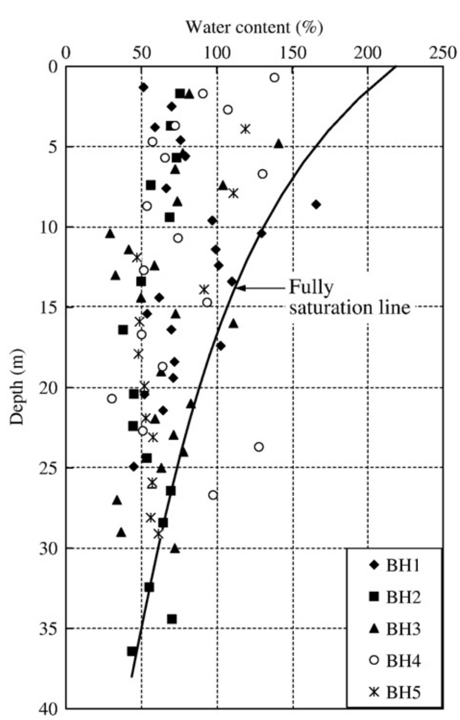

Fig. 11. Variations in water content with the embedment depth.

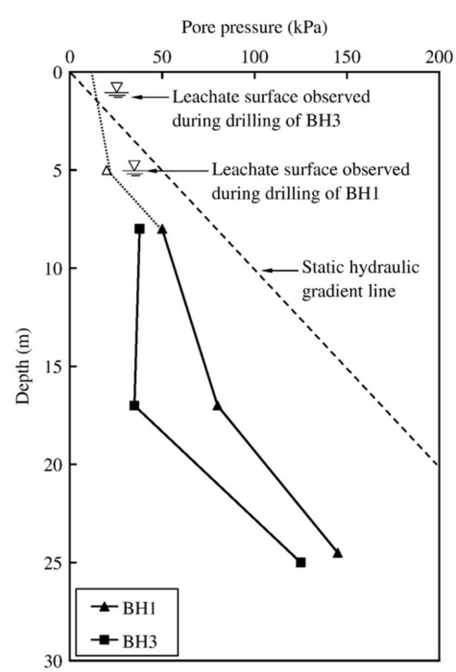

Fig. 12. Profiles of pore pressure measured in boreholes BH1 and BH3.

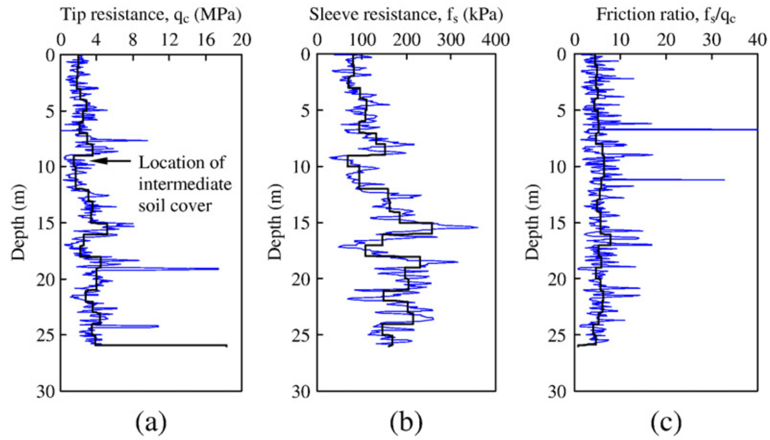

Fig. 13. Results of cone penetration tests from J1.

As shown in Fig. 13(b), the values of sleeve resistance, f_s, against depth generally varied from 50 to 300 kPa with the middle values between 80 and 250 kPa. The variation of f_s with the depth shows a similar trend to that of q_c. As shown in Fig. 13(c), the middle values of friction ratio, (f_s/q_c), generally fall between 4% and 6%. The variation of friction ratio, (f_s/q_c), with depth also shows a similar trend to that of q_c. By comparing the profiles of q_c and f_s with the corresponding pore pressure profile shown in Fig. 12, it can be seen that the section with a significant increase in both q_c and f_s with depth (i.e., from 12 to 18 m) coincides with the unsaturated zone. This indicates that the significant increase in both q_c and f_s within the zone are primarily the result of the increase in overburden pressure. In addition, the section without an increase in either q_c or f_s with depth (i.e., below 20 m) was located in the saturated zone near the landfill bottom where pore pressure significantly increase with depth. The cone penetration within the bottom saturated zone was likely performed under undrained conditions because fine cinders and dust dominated the MSW composition (see Figs. 2 and 4).

Fig. 14 shows a comparison of the CPT result from J2 with that from J1. It should be noted that J2 penetrated through the MSW with fill ages ranging from 0 to 6.8 years, while J1 penetrated through the MSW with fill ages from 6 to 12.8 years. To be clear, the middle lines of the curves of q_c, f_s and f_s/q_c were plotted in Fig. 14 for comparison. The results show that for most of the depths the values of q_c and f_s obtained from J2 are generally lower than the corresponding values from J1, even with the lower pore pressures in J2 (see Fig. 12). An exception occurs in the depths from 6 to 12 m in Fig. 14. The exception was attributed to the local placement of rigid building waste at J2. The greater values of q_c and f_s for the old MSW are consistent with the increase of shear strength with fill age for a mean stress level greater than 50 kPa (see Fig. 7(a), (b), (c) and (d)). In addition, the values of friction ratio (f_s/q_c) from J1 are generally less than those from J2. This occurs because q_c is about 20 times greater than f_s, and hence dominates the ratio. The above discussion indicates that there is a possibility to correlate the cone penetration test results with the shear strength properties measured in the laboratory. Further field and laboratory studies are encouraged for this topic.

7. Slope stability analyses

7.1. Effect of shear strength parameters on the factor of safety

The measurements of shear strength and leachate level provide the basic information required to analyze the slope stability of the

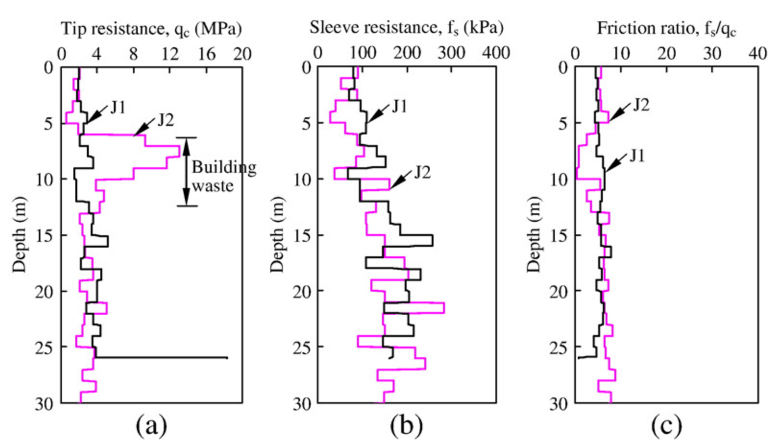

Fig. 14. Comparison of cone penetration test results between J1 and J2.

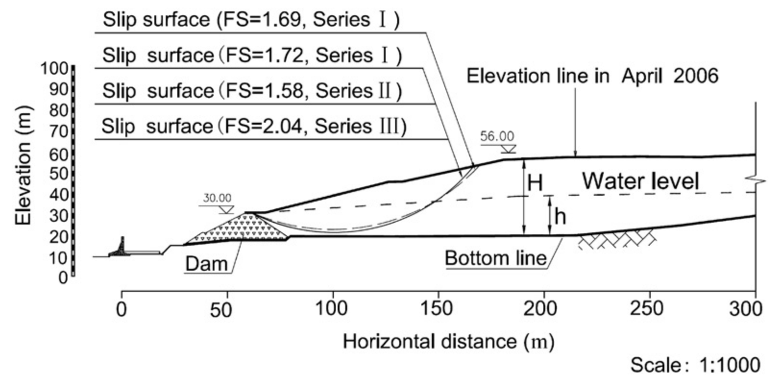

Fig. 15. Results of slope stability analyses on the Suzhou landfill.

existing Suzhou landfill. Fig. 15 shows the cross-section of landfill with a minimum potential of slope stability. The leachate level in the landfill was plotted based on the field measurements of pore pressure. In accordance with the measurements on the density of MSW, a constant value of unit weight was assumed for all layers of MSW (i.e., 11 kN/m^3). It was assumed that the critical slip surface would not pass through the rock-fill dam or the gravelly clay layer underneath the bottom of the landfill because of their high shear strengths relative to the MSW. It is noted that there was no weak artificial liner under the bottom of the landfill. The slip surface was assumed to be circular, and the pattern search for “location” was used to find the center and radius of the slip circle. A limit equilibrium method, (i.e., Bishop Simplified method), was used to calculate the factor of safety, F_s.

Three series of shear strength parameters (see Table 3) were used for the slope stability analyses. For Series I, the dependence of shear strength parameters on the fill age of waste, as obtained in this study, was considered. The shear strength parameters corresponding to a strain level of 10% in Fig. 8 were used for the analyses as suggested by Feng (2005). For Series II, the shear strength parameters recommended by Dixon and Jones (2005) were used. For Series III, the shear strength envelope recommended by Kavazanjian (2001) was used for the slope stability analyses. Fig. 15 shows that the critical slip surfaces obtained from Series II and III coincided with each other, and the slip surface from Series I does not differ much from the other two. The minimum values of F_s corresponding to the three series (I, II, and III) were 1.69, 1.58 and 2.04, respectively. If the critical slip surface of Series II and III was specified for the analyses, the F_s corresponding to Series I was equal to 1.72, being slightly greater than the corresponding minimum F_s value. By way of comparison, the parameters recommended by Dixon and Jones (2005) appear to result in a slight under-estimation of F_s, and the parameters recommended by Kavazanjian (2001) appear to result in an over-estimation of F_s. All three values of F_s were greater than 1.0, being consistent with the current stable state of the existing landfill. Here it is worthwhile to point out that the value of F_s could be affected by the potential anisotropy in the shear strength of the waste. A further investigation on this should be encouraged.

Table 3
Parameters used for slope stability analyses and results

Series no.	Sub-layer of MSW	Elevation or depth (d) of sub-layer (m)	Unit weight (kN/m^3)	Shear strength parameters		Factor of safety (FS)	
				c (kPa)	φ (°)	Minimum value	For a specified slip surface
I	LW4	48–65	11	23.3	9.9	1.69	1.72
	LW3	40–48	11	24.0	17.6		
	LW2	28–40	11	16.4	26.1		
	LW1	12–28	11	0	26.0		
II	LW1–LW4	12–65	11	5	25	1.58	1.58
III	LW4	$d<3$	11	24	0	2.04	2.04
	LW1–LW4	$d\geq 3$	11	0	33		

7.2. Influence of leachate level on the factor of safety

The leachate level in the landfill changes as a result of seasonal moisture cycles and ongoing water accumulation. The influence of the leachate level on the stability of the Suzhou landfill was investigated by performing further slope stability analyses. The shear strength parameters corresponding to a strain level of 10% were used for the analyses. Fig. 16 shows the change in F_s with the normalized height of leachate level (i.e., h/H), where h is the height of leachate mound and H is the

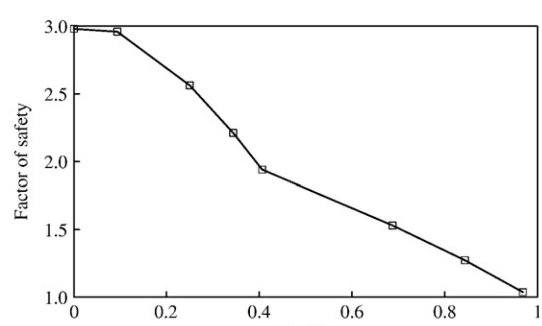

Fig. 16. Influence of leachate level on the slope stability of the Suzhou landfill.

maximum thickness of the landfill. When the leachate level is located at the bottom of the landfill (i.e., totally unsaturated condition), the minimum F_s for the landfill is close to 3. An increase in the normalized height of the leachate level results in a significant decrease in the F_s. When the leachate level reaches the top surface of the landfill (i.e., totally saturated condition), the minimum F_s for the landfill is close to 1. The analysis results suggest that the leachate level in the landfill should be controlled at a height less than 70% of the thickness of the landfill in order to meet the condition for a safe design F_s value of 1.4.

8. Summary and conclusions

On the basis of the field and laboratory study on the waste strata of MSW and the leachate levels at the Suzhou landfill, the following conclusions can be drawn:

(1) The waste material in the landfill can be sub-divided into several strata corresponding to different ranges of fill age. Each of the waste strata has its individual composition, volume-mass properties and other engineering properties.
(2) The triaxial test results showed that each of the MSW samples exhibited a strain-hardening and contractive behavior. The shear strength envelope for the MSW depends on the strain level allowable in the design of a landfill.
(3) For a given strain level between 5% and 20%, it was found that the mobilized cohesion decreased with an increase in the fill age of the MSW, and the mobilized angle of internal friction increased with the fill age. For a mean stress level greater than 50 kPa (i.e., $p' \geq 50$ kPa), the shear strength of the recently-placed MSW appears to be lower than that of the older MSW.
(4) The cone penetration results on the old MSW resulted in a higher tip resistance and a higher sleeve resistance than that through the recently-placed MSW. These results are basically consistent with the shear strength measurements. The cone penetration through the MSW in the landfill resulted in a friction ratio (f_s/q_c), ranging from 4% to 6%.
(5) The hydrogeology system in the Suzhou landfill was complex. The field measurements of pore pressures and water content revealed a perched leachate mound above an intermediate cover of soils and a substantial leachate mound at the bottom of the Suzhou landfill. Results from slope stability analyses demonstrated that the substantial leachate head in the landfill can produce a threat to overall slope stability.
(6) The shear strength parameters recommended by Dixon and Jones (2005) and Kavazanjian (2001) may result in a slight under-estimation and an obvious over-estimation on the slope stability of the Suzhou landfill, respectively, in comparison to the shear strength parameters obtained in this study.

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