TECHNICAL ARTICLE
Landslides in landfills

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ABSTRACT

In general, MSW is a non-textbook material, being highly fibrous, heterogeneous, erratic, highly compressible, and displaying significant long-term settlement caused by plastic creep and decomposition. Its strength is significantly affected by its fibrosity and its degree of decomposition. Neither undisturbed sampling nor field testing of shear strength is practical. Laboratory testing of more or less undecomposed MSW can be carried out meaningfully only in large-scale equipment developed specifically for geotechnical tests such as consolidation, simple shear, ring shear and tension tests. The effects of decomposition cannot, however, be accounted for by such tests, unless the test specimens represent truly decomposed MSW. The present study suggests that a weakened zone may often develop along the base of MSW landfills as a result of advanced decomposition there. If the material has been tested in its more or less undecomposed state, which seems always to be the case, it is likely that the measured strength is not relevant, being too high and thus leading to unrealistically high factors of safety.

1 INTRODUCTION

The geotechnical behaviour of municipal solid waste (MSW) has attracted increased attention over the past two or three decades as a result of several catastrophic landfill failures worldwide. For example, a waste slide in the Philippines in 2000 claimed more than 220 lives, with an estimated 200-800 people missing. In 1996, a failure of a landfill in La Coruna, Spain, led to more than 100,000 tonnes of MSW sliding nearly a kilometre, coming to rest at a short distance from the Atlantic Ocean and narrowly avoiding what could have been one of the greatest environmental disasters in history. Although widely separated geographically, these events had much in common. Both landfills were large and their ages (approximately 30 years) were comparable. The age issue is particularly interesting since, whereas one would expect the foundation soils to gain strength with time due to consolidation beneath the waste, it appears that the opposite is the case with MSW material, i.e. the material in the basal failure zones seems to become weaker with time as it continues to decompose.

Most of the as-placed constituents in waste fill have a high to extremely high aspect ratio (greatest dimension ÷ least dimension), i.e. the “degree of fibrosity” is generally high. The undecomposed MSW therefore behaves much like a reinforced material, having discontinuous “fiber” reinforcement generally oriented in a direction parallel to the bedding of the material as placed.

Since MSW material is subject to decomposition, its geotechnical properties will change with time. The amount of time involved will vary considerably, depending on the nature of the MSW constituents, from a few years to perhaps several hundred or even one thousand years. Weakening of the landfill will also result if (i) the MSW material is mixed with compost or other weak materials, (ii) if it is subject to smouldering fires, not uncommon in landfills, or (iii) if it has been subject to scavenging and thus removal of reinforcing elements such as construction debris.

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The fiber resistance of MSW accounts for the frequently observed phenomenon of high vertical (or near vertical) cuts in landfills. Since, however, MSW decomposes with time, unsupported slopes cannot be expected to remain stable indefinitely. The stability of the slope will therefore gradually deteriorate, and this must eventually lead to failure.

2 MODES OF FAILURE

The conventional approach to the analysis of slides in landfill is to treat MSW as a mineral soil and to model such slides on the basis of regular soil mechanics principles, such as shown in Fig. 1. For example, Merry et al. (2005), on analyzing the 2004 Payatas, Philippines, slide described in the review below, considered the section shown in Fig. 1 to be representative of the failed MSW slope. The factor of safety was calculated using Spencer’s method. The shear strength parameters for the MSW used in the effective stress analysis were a cohesion intercept of 19 kPa and a friction angle φ' of 28°. Their analysis was thus based on a conventional soil mechanics approach. As such, and as indicated in Fig. 1, the displacement during a conventional slide would come to a stop when the final configuration and soil strength combine to produce a factor of safety just exceeding 1.0. In this connection, reference is also made to the well-known 1916 Gothenburg Harbour slide (e.g. Tschebotarioff 1951, p. 178).

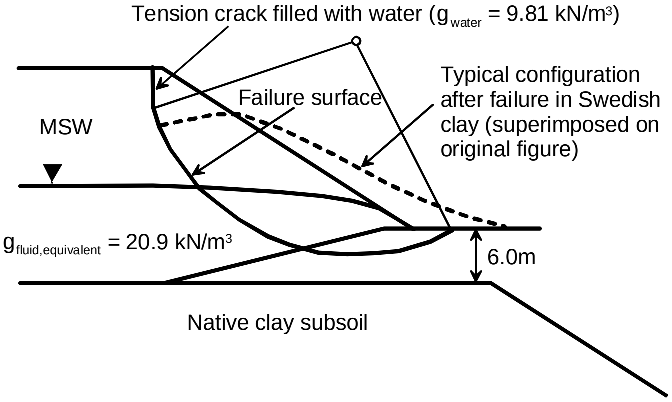

Fig.1 Two-dimensional cross section of slope evaluated in stability analyses (Merry et al. 2005).

In the present paper, attention is drawn to the many peculiarities affecting MSW geotechnical behaviour, such as fiber reinforcement, decomposition, scavenging, smouldering fires, and mixing with weaker fill materials. Also important is the observation that landfills are often located on incompetent or sloping (or both) foundation soils.

Scavenging can be expected to accelerate decomposition significantly. In this connection, reference is made to Merry et al.’s (2005) description of scavenging, one result of which is that “items such as wood or metal building materials, cardboard, and intact bottles are quickly segregated and reused or recycled, leaving a waste stream that is predominantly organic matter”.

The most critical zone of older landfills would be their bottom (i.e. the oldest) portion, which is the portion that is exposed to the highest pressure and temperature, has the highest moisture content, the lowest permeability, and a high content of anaerobic micro-organisms enhancing bacterial activity. Despite its low permeability, drained conditions may prevail even in this bottom zone as the material is decomposing. However, in the event of a sudden addition of fill above or as a result of an excessive rainfall, high pore pressures may be induced there, which may in turn cause undrained failure and a flow slide. Such a flow slide would not come to an immediate stop (such as in Fig.1 or in the Gothenburg slide), but would continue flowing downhill for a considerable distance (such as the Payatas failure).

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3 REVIEW OF SIX MSW CASE RECORDS

Rumpke: MSW Slope Failure

A landslide involving in excess of one million cubic metres of MSW occurred in 1996 at the Rumpke Sanitary Landfill near Cincinnati. Landfill operation personnel first noticed cracks in the cover on the top of the landfill. The cracking continued over the next five days, at which time cracking of the cover as well as soil slippage was observed at the toe of the slope. Several of the cracks were expanding at or near the top of the landfill and larger-scale horizontal movements were occurring at the toe of the slope.

This failure is widely considered to have been a translational retrogressive slide along a weak layer of "brown native soil" directly beneath the bottom of the waste (e.g. Schmucker and Hendron, 1998, Stark et al. 2000, Eid et al. 2000).

The descriptions of this slide certainly indicate a translational retrogressive type of failure, occurring along a plane of weakness at the bottom of the landfill as described by Schmucker and Hendron and Eid et al. However, the present authors believe that this zone of weakness likely existed in the waste itself and not in the native soil beneath. It is possible for such a material to decompose to the state of a slime, in which case its strength could become extremely low.

The disposal at the site began in the 1930's as part of the operation of a swine farm (Schmucker and Hendron 1998). Landfilling operation, which initially consisted of pushing waste over the edge of an existing ravine, began in 1955 for the purpose of disposing waste compost remaining from the hog-raising operations. The initial operation of the landfill involved little excavation or compaction of waste and relied on the in-situ clays as a natural liner.

According to Schmucker and Hendron's account of the failure, there were substantial quantities of fluid flowing from the toe area of the landfill, and photographs indicated that the leading edge of the landslide was completely soaked with "watery-grey" mud. A large volume of leachate (black fluid) was observed to be flowing under high pressure through cracks that had formed in the solid waste materials that were moving horizontally across the access road at the toe of the slope. Post-failure photographs taken of the landslide indicated that the leading edge of the landslide was essentially liquefied waste. It was reported that "a pickup truck carried with the leading edge of the landslide was completely soaked with watery-grey mud". At the top of the slide, steam was emanating from cracks in the landfill.

It seems clear from these descriptions that there must have been a zone of highly decomposed MSW material near the bottom of the landfill, probably underlain by or mixed with waste from the hog-raising operation. That operation may have taken place over a period of twenty years in which case a large amount of very weak, decomposable waste may have been present. The descriptions also indicate excessively high pore water (leachate) pressures to be involved.

Schmucker and Hendron's analysis of the main slide gave an average required friction angle φ' (for F = 1.0) of 15° to 19°, depending on the assumed leachate level at the time of the slide.

Leuwigajah Dump Site, Bandung, Indonesia, 2005

In February 2005, the Leuwigajah dumpsite in Bandung, Indonesia, collapsed causing an avalanche of some 2.7 million cubic metres of waste, killing 147 people (Kölsch et al. 2005). The geometry used by Kölsch et al. in their analysis is shown in Fig. 2 (based on their figs. 3 to 5). The groundwater (or leachate) level used in their study (GWL1) corresponded to a pore water pressure of approximately 150 kPa, as shown. It seems clear that the failure occurred within a thin, very weak layer near the base of the landfill.

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Kölsch et al. concluded that the Leuwigajah failure most likely was "triggered by water pressure in the soft subsoil in combination with a severe damage of reinforcement particles due to a smouldering landfill fire". However, in view of the fact that the subsoil had been consolidated under considerable overburden stress, ranging between 500 and 1000 kPa, for about 30 years, it is unlikely that the seat of failure was located within this zone.

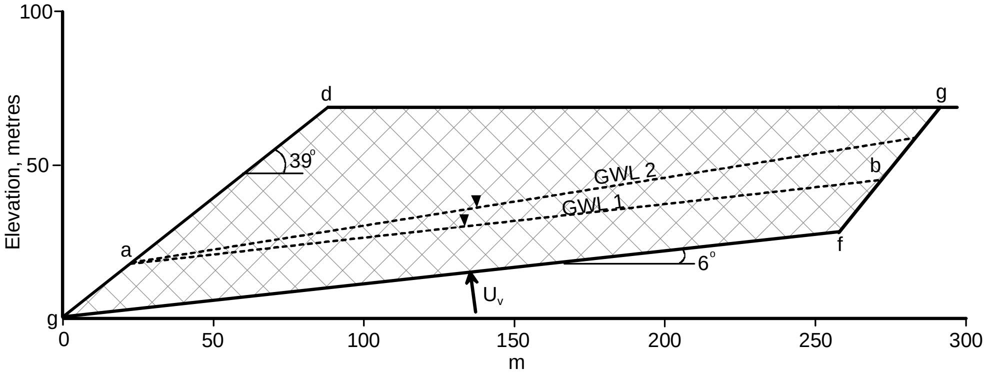

Fig.2 Section through Leuwigajah dumpsite, Bandung (Kölsch et al. 2005)

On the other hand, considering that precipitation in the area of the slide is between 1500 and 2000 mm/year and that heavy rainfall and thunderstorms are common during the wet season, there seems little doubt that a high pore water pressure was the critical factor. However, as with the Rumpke slide, the weak zone was in all probability located within the decomposing waste, and not in the mineral soil beneath the landfill base. If the groundwater level was located at GWL 2, a mobilized angle of friction of 15º could have just triggered a slide along the weak zone.

Witnesses to the slide report "a roll of thunder somehow like an explosion… observations indicate that the waste came down quite similar to an avalanche". In this connection, reference is made to Merry et al.'s (2005) description of scavenging, one result of which is that "items such as wood or metal building materials, cardboard, and intact bottles are quickly segregated and reused or recycled, leaving a waste stream that is predominantly organic matter".

Ümbaniye Dump Site, Istanbul

A major failure was experienced at the Ümbaniye Dump Site in Istanbul in 1993. The failure was very sudden and the decomposed waste mass moved down the valley at a high speed for approximately 500 metres. The topography of the failure and the critical cross section are shown in Fig. 3.

The failure was translational in nature and involved the movement of 470,000 m^3 of waste. The section in Fig. 3 is what was used by Koerner and Soong (2000) and labelled "critical 2-D cross section after the failure". The sliding waste buried numerous homes in its path and resulted in the loss of 27 lives. Excessive leachate level buildup within the old decomposed waste caused by water infiltrating from adjacent surface water ponds was likely the triggering mechanism of the failure (Koerner and Soong, ibid).

The mode of failure, as described above suggests that the waste mass was moving on a wet lubricated layer, e.g. on a zone of highly decomposed, mostly organic waste material. With a groundwater level such as that shown in Fig. 3, a mobilized angle of friction of 17º would correspond to a factor of safety of 1.0.

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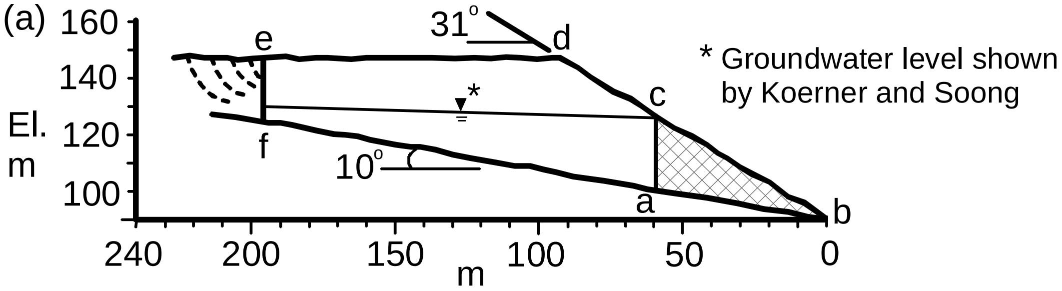

Fig. 3 Ümbaniye Dump Site, Istanbul, section of fill involved in the slide (Koerner and Soong, 2000)

La Coruna, Spain

In October 1996, a massive waste slide occurred at the Bens municipal dump near La Coruna, Spain. The following comments are in reference to this failure and are quoted from TIME (7 October 1996), Financial Times (12 October 1996) and from Genske (2003).

> "… a landslide that some locals had predicted for years. The avalanche began when deep fissures appeared in the Bens municipal dump…. Heavy rains are being blamed for the instability. The top has always leaked streams of foul-smelling liquids … a great heaving mass … poured down the valley, swallowing sheds and vehicles… with a huge roar, part of the giant tip overlooking O Portino broke off, and a wall of rubbish 50 m high slid down to the rocky Atlantic seafront…sites like this, without facilities for drainage … the site … has been operating for 17 years, accumulating rubbish from the metropolitan area's 400,000 residents…an estimated 100,000 tonnes of garbage sheared off the edge of the tip which, swollen with 22 years of refuse, had risen to a 14-storey skyscraper…the avalanche flattened everything it met as it careered downhill for the best part of a kilometre to the sea, coming to rest a short distance from the Atlantic Ocean and narrowly avoiding what would have been one of the greatest environmental disasters in history".

Again, this mode of failure seems to be that of a waste mass moving on a weakened layer of decomposed MSW material.

Payatas, Philippines

"In the Payatas slide, more than 220 people were found dead and an estimated 200-800 persons were still missing in 2004. The major reason for the failure was considered to be the low waste density resulting from the composition of the waste, which was characterized by a high proportion of plastics and organics and a total absence of other materials, such as paper, glass and metals. The impact of low waste density was amplified by heavy rainfall, which is characteristic for tropical locations" (Kölsch and Ziehmann 2004). 13,000 to 16,000 m^3 of waste was involved in the slide (Merry et al. 2005). The waste stream consisted predominantly of organic matter, i.e. there was little if any cardboard, plastic, copper wire, glass bottles, wood and metal building materials for shanty homes, or any edible items.

At daybreak, there were loud cracking sounds and water was observed leaking from cracks in the landfill. A large mass of waste came down the hillside similar to a debris flow, covering all the homes and people in its path.

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It seems highly unlikely that the mechanism of this slide as described above can be represented by a circular failure surface such as that shown by Merry et al. (2005). Such failures, originally introduced by Fellenius et al. (1922) in connection with numerous failures in Swedish marine clays, could not in any way be considered to be representative of flow slide failures in landfills such as, for example, this failure.

Another indication of the nature of the Payatas failure is the description by Kölsch and Ziehmann as a large mass of waste coming down the hillside: “On 10 January around 5 a.m. … a ‘garvalanche’ (i.e. garbage avalanche) buried the scavengers’ cottages and part of the Payatas & settlement area under 10 m of waste. An area of around 30,000 m^2 in front of the toe of the slope was completely covered by waste and debris.”

Ano Liossia, Athens

The MSW of the Greek capital Athens is disposed of at several landfills, one of these being the landfill at Ano Liossia. The area of this landfill is about 50 ha (about 125 acres) and its height varies between 60 and 80 metres. The site is surrounded by chains of hills.

In March 2003 the eastern slope of the landfill failed, covering the 20-metre deep notch between the slope and the recycling facilities behind with waste. Approximately 800,000 m^3 of waste moved, leaving a 300 to 400 m wide gap in the slope behind.

According to Kölsch and Ziehmann (2004) “water was very likely the cause as it is in all cases of landfill failures, but no significant water outlet from the failing slope had been reported by the operator…it has not become finally clear why the slope failed…it may also be a consequence of a fire which occurred two weeks before in the landfill stretch concerned.”

The combination of heavy rainfalls, no significant water outlet, the high proportion of organics, the thickness and age of the landfill, and the loss of any reinforcing constituents by fire, in all probability led to the existence of a highly decomposed layer of MSW at the base of the waste, as described in the sections above. Such decomposition seems to fully explain the nature of the slide, including the non-existence of any significant water outlet from the failing slope.

LESSONS LEARNED

In their final chapter, entitled “Lessons learned”, Schmucker and Hendron (1998) listed the following four lessons learned from the Rumpke landfill slide:

1. It is important to quantitatively understand the relationship between pore pressures in the landfill and factor of safety of specific landfill slopes.
2. MSW is a strong material under static and unsaturated conditions.
3. It is important as well to understand the actual geometry of the slope in making the slope stability calculations.
4. Large landslides in landfills may occur very suddenly; initial surface manifestations of the impending failure may not be very significant and could be misunderstood. Consider installation of instrumentation.

Lessons Nos. 1, 3 and 4 have certainly been confirmed by the present study of several landslides in landfill. Lesson No. 2, however, has been found to apply only to undecomposed MSW above the ground water (leachate) level. The flow-slide behaviour during actual landfill failures demonstrates that the material involved in these failures behaves more like a liquid, the slide occurs very suddenly and the sliding body moves at a considerable speed over a distance of several hundred meters.

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One major and very important conclusion that can be drawn from this study is that the critical portion of a landfill with respect to stability appears to be the bottom (i.e. the oldest) portion of it, which is the portion that is exposed to the highest pressure and temperature, has the highest moisture content, the lowest permeability, and a high content of anaerobic micro-organisms enhancing bacterial activity. Meaningful geotechnical investigations of landfills should therefore concentrate on this zone rather than on the upper less decomposed portions of the fill. One example of advanced decomposition of the bottom portion is the Fresh Kills landfill, opened by New York City in 1948 on Staten Island. The following are excerpts from a description by Rathje (1991) of the Fresh Kills refuse:

> "The refuse near the top looked normal…but within 8 to 12 metres of the level of the stream…things changed…all the excavated debris was moist and newspapers were damp…another 5 metres down and the refuse was dripping wet…still another few metres there was only gray slime, studded with lumber remnants…metal cans, bottle glass, plastic jugs and utensils and toys…but no food debris or yard wastes, and practically no paper…the gray slime had to be the result of biodegradation."

SUGGESTED GEOTECHNICAL INVESTIGATION OF OLD LANDFILLS

Undisturbed sampling of MSW is impracticable. Conventional field investigations such as SPT, vane testing, CPT etc. are also impracticable. However, much can generally be learned from obtaining the following information:

1. Determine the original ground from topographical maps of the area
2. Determine the age of the MSW
3. Determine the method of placing and the type of MSW placed
4. Check the existence of old borings and descriptions of any samples taken
5. Check into the history of the landfill, particularly with respect to any scavenging
6. Obtain a record of rainfalls over the period since placing started
7. Carry out a topographical survey of the landfill
8. Inspect the landfill surface for fissures, cracks, any movements
9. Inspect for any leachate leakages and any foul odours
10. Obtain samples of the MSW by bucket augering or sonic drilling, particularly from the bottom portion
11. Determine the thickness of the MSW
12. Determine the pore pressures in the lower portion of the landfill

Items 1 to 9 do not require any special equipment and can probably be done without undue cost for most, if not all, landfills. Items 10 and 12, on the other hand, definitely would require special and costly equipment and would only be carried out if items 1 to 9 should indicate a high risk of failure.

SUMMARY AND CONCLUSIONS

Several characteristics set MSW materials apart from conventional inorganic soils: fibre reinforcement, high aspect ratios, high compressibility, long-term plastic creep, long-term decomposition, and ravelling. In its undecomposed state MSW – as placed – is a discontinuously reinforced material, the reinforcement generally being parallel to the direction of the bedding.

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One major difference between MSW and conventional inorganic soils is that undecomposed MSW is a reinforced material. Another is that it is subject to decomposition. And a major difference between MSW landfills and conventional embankments such as highways and dams is that – more often than not – MSW landfills tend to be located on incompetent foundation soils.

Other problems are (i) the mixing of the MSW with compost or other weak materials, such as in the case of the Rumpke landfill, (ii) the occurrence of smouldering MSW fires (such as in the case of the Ano Liossia landfill) which by consuming combustible constituents will weaken the MSW, and (iii) the effects of scavenging, which tends to result in the removal of reinforcing elements and leaving material that decomposes more readily, i.e. eventually leaving unreinforced slimy material of low strength.

As existing landfills continue to decompose, landfill failures can be expected to continue to occur, particularly if the landfills are located on sloping impervious ground (such as the Ümbaniye failure) or if they are located in an area receiving excessive rainfalls. Failures may initially occur in the form of gradual shear deformations. Eventually, a flow slide type of failure along this layer can be expected to occur as the height of the landfill increases, as the decomposition at the base continues, and as heavy rainfalls are experienced.

Analyses of landfill slides on the basis of conventional soil mechanics principles are not applicable, considering the highly unconventional behaviour of MSW materials.

Cases of high and very steep, but stable, landfill slopes are sometimes reported in the literature. The stability of such slopes is a function of the considerable fibrous (tensile) resistance of the more or less un-decomposed MSW constituents. Such slopes will therefore not remain stable indefinitely, but will start to fail as the MSW material starts to decompose.

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APPENDIX

With the permission of the authors, the editor of ISSMGE Bulletin adds photographs of the Leuwigajah landfill in Indonesia that were taken in 2006 after its failure in 2005.

Photo 1 Top scarp of failed landfill

Photo 2 Flow and deposit of waste