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Analysis and Modelling of Slope Failures in Municipal Solid Waste Dumps and Landfills: A Review

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ABSTRACT

The essential issues solved by geoenvironmental engineers relate to the assurance of uncontaminated regions of the subsurface just as the remediation of locales of the subsurface that have been sullied by releasing waste materials, spilling over the ground and underground stockpiling tanks and penetration of pesticides. In city areas, garbage and waste materials are generally dumped into landfills. A landfill site, which is otherwise called a trash dump, is used for the disposal of waste materials by burial. A safe landfill is a deliberately built sorrow in the ground into which wastes are put. The principal objective is to stay away from any water driven association between the wastes and the surrounding environment especially groundwater. This paper discusses landfill, in terms of its construction, stability and failure. The analysis and modelling of the landfill failure occurred in different countries like Poland, Turkey, Israel, the Philippines, China and Sri Lanka which are discussed.

INTRODUCTION

The primary problems addressed by geoenvironmental engineers pertain to the protection of uncontaminated regions of the subsurface as well as the remediation of regions of the subsurface that have been contaminated by one or more events which involve industrial chemical spills, leaking waste containment facilities, leaking above-ground and underground storage tanks, and infiltration of pesticides.

A landfill site which is also known as a garbage dump or dumping ground is a site for the disposal of waste materials by burial. Some landfills are also used for waste management purposes, such as the temporary storage, consolidation and transfer, or processing of waste material. Processing of waste materials includes sorting, treatment and recycling. Unless they are stabilized, these areas may experience severe shaking or soil liquefaction of the ground in case of a large earthquake. A secure landfill is a carefully engineered depression in the ground into which wastes are put. The main objective is to avoid any hydraulic connection between the wastes and the surrounding environment particularly groundwater.

A landfill is a bathtub in the ground; a double-lined landfill is one bathtub inside another. Bathtubs leak two ways, one out the bottom and another over the top. An important feature in the identification and assessment of potential failure mode is the fact that both covers and liners for modern landfills are typically multilayer composites composed of both soil and geo-synthetic materials. The liner system contains several interfaces whose resistance against interface shear stresses may be low, and thus these act as possible failure surfaces. Additionally, all classical geotechnical failure modes are possible depending on site-specific conditions (usually involving saturated fine-grained soils) and the placement and geometry of the waste mass. Landfill failure can be studied by carrying out the analysis and modelling of failure surfaces. For these computational techniques, computer programs are used. This paper discusses landfill, in terms of its construction, stability and failure. The analysis and modelling of the landfill failure occurred in different countries like Poland, Turkey, Israel, the Philippines, China and Sri Lanka which are given in Table 1.

ANALYSES OF LANDFILL SLOPE FAILURES

Sarihan & Stark (2008) carried out a back analysis of landfill failures and investigated the shear strength of municipal solid waste (MSW) using the techniques of back analyses for different slope failures associated with wastes across the world. Slope failure for landfills may be resulted due to heavy rainfall or the development of tension cracks. Sometimes it may be associated with the harmful effects of leachate. Leachate is a widely used term in the environmental

Table 1: Historical record of slope failures in municipal solid waste dumps and landfills.

Year	Location	Failure Reason	Reference
1965	Warsaw, Poland	Steep slopes, excessive leachate level	Bouzza & Wojnarowicz 2000
1988	California, USA	Sliding along interfaces within the composite liner system	Mitchell et al. 1990
1993	Istanbul, Turkey	Heavy rains, excessive leachate level	Kocasoy & Curi 1995
1996	Cincinnati, Ohio, USA	Softening of underlying native soils	Stark et al. 2000
1996	Mahoning, Ohio, USA	Failure along wet bentonite layer of the unreinforced GCL	Stark et al. 1998
1997	Hiriya, Israel	Steep slopes, lack of drainage controls, high moisture content	Huvaj-Sarihan & Stark 2008
2000	Payatas, Manila, Philippines	Failure along MSW and clay subsoil induced by heavy rains	Huvaj-Sarihan & Stark 2008
2005	Bandung, Indonesia	High water pressure in the soft subsoil	Koelsch et al. 2005
2008	Shenzhen, China	High water level within landfill	Peng et al. 2016

sciences where it has the specific meaning of a liquid that has dissolved or entrained environmentally harmful substances that may then enter the environment. It is most commonly used in the context of land-filling of putrescible or industrial waste. An investigation found that the landfill doesn't have an engineered bottom liner, final cover or leachate and gas control systems. Analysis of failure slopes of Gnojna Grora landfill in Poland, Istanbul Landfill in Turkey, Hiriya Landfill in Israel, and Payatas Landfill in the Philippines are discussed below.

Gnojna Grora Landfill in Poland

Bouzza & Wojnarowicz (2000), described the Gnojna Grora Hill landfill, in Warsaw, Poland. The archaeological work performed for this landfill revealed that the landfill dates to the 14th century which showed that it is an old landfill without any liner or cover system layers. In 1965, cracks were observed in nearby buildings due to the movements in the landfill which showed that fill is composed of large amounts of demolition debris composed of old domestic MSW. The unit weight of the waste material was estimated to be 17 kN/m^3 as the waste is mixed with demolition debris. Groundwater or leachate level was found to be 3 to 5 meters below the ground surface based on piezometer records (Fig. 1a).

To back-calculate, the Municipal Solid Waste (MSW) was assumed to exhibit a cohesion intercept (c') of 0 kPa and the back-calculated friction angle (φ') is 21º. They estimated that the average effective normal stress and corresponding back-calculated shear strength on the observed failure surface through the waste are 106 kPa and 40.7 kPa respectively. The shear strength of MSW decreases with age (Siegel et al. 1990, Brandl 1998, Gabr et al. 2002, Reddy & Bogner 2003). So it is acceptable to assume cohesion intercept is equal to 0 for a 300 years old MSW demolition debris mix and back-calculate the friction angle.

Istanbul Landfill in Turkey

This landfill of Turkey described by Kocasoy & Curi (1995) and Koerner & Soong (2000) which is about 30 km away from the city centre in Istanbul (Turkey), operated since 1976. Their study showed that maximum MSW slope height was about 45 m, with steep front slopes of up to 45 degrees or even more and MSW was placed without any liner system. Waste in this landfill was not compacted and not covered with soil. Landfill failure occurred on April 28, 1993, and resulted in 27 casualties and involved approximately 500,000 m^3 to more than 1,000,000 m^3 of waste. Fires were known to be burning on the surface of the waste at several places during most of the year before the slide which is shown in Fig. 1b reported by Kocasoy & Curi (1995).

In this case, the explosion could not have been the main cause of the movement of the waste. They also confirmed that the heavy rains, and excessive leachate level built up within the old decomposed waste caused by water infiltrating

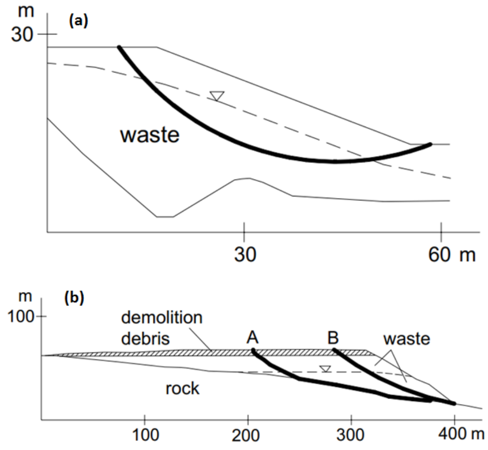


Fig. 1: Approximate slope profile of (a) Gnojna Grora Landfill (Poland) (b) Istanbul Landfill (Turkey).

Fig. 2: Failure of Hiriya Landfill (Israel).

from the adjacent surface water ponds were likely the triggering mechanism, together with recently placed demolition debris on top of the waste. As shown in Fig. 1b, the waste mass there is impermeable rock. The authors assumed the unit weight of 11 kN/m^3 because no further information is available. It is assumed that the failure surface is the most reliable because it is based on their observations at the site and data they obtained from the municipality of Istanbul. A and B represent the non-circular and circular failure surface respectively.

Hiriya Landfill in Israel

The Hiriya landfill in Israel failed in 1997 due to steep slopes, lack of drainage controls and high moisture content which is located east of Tel-Aviv which is an open area at the convergence of the Shappirim River and the Ayalon River (Fig. 2). Isenberg et al. (2004) investigated that the dump has been used for the disposal of MSW for the greater Tel-Aviv area for decades. They also confirmed that the landfill does not have an engineered bottom liner, cover and gas control systems.

Prayatas Landfill in Philippines

The Prayatas Landfill is located in the NE part of Manila. It has been in operation since 1973 and about 1500 tonnes of MSW are placed since 1996. The exact mechanism of failure is not known but several factors like heavy rainfall may lead to cause saturation of MSW and water ponding on top of the slopes were reported by Merry et al. (2005).

MODELING OF LANDFILL SLOPE FAILURES

Guangming Landfill at Shenzhen, China

Ouyang et al. (2017) studied catastrophic landslide of the construction waste landfill at Guangming, Shenzhen, China

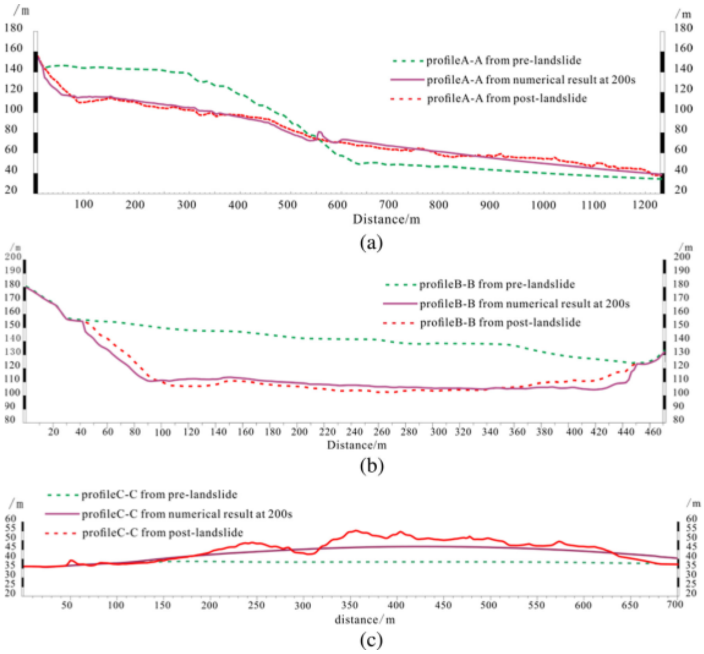


Fig. 3: Comparison of numerical results and field investigation results along (a) the main sliding profile A-A, (b) transverse profile B-B, and (c) transverse profile C-C for Guangming landfill at Shenzhen, China (Ouyang et al. 2017).

occurred in December 2015 which destroyed 33 buildings and caused 69 deaths (Yin et al. 2016). This type of landfill occurred without the involvement of rainfall or heavy rainfall with H=111 m and L=1.2 km. The mesh-free Smooth Particle Hydrodynamics (SPH) method is applied in modelling the landslide over natural terrain.

Investigation for this landslide showed that the soil is almost fully liquefied in the sliding surface due to plenty of water. Thus, it is highly possible that plenty of water was stored in the waste fill. Unmanned Aerial Vehicle (UAV) used to collect the pictures two days before the event and three days after the event. Snapshots of the computed flow height were collected at different time intervals. Graphs were plotted in which the author compared the profile before and after the landslide event (Fig. 3).

Liang et al. (2019) studied the Shenzhen landslide based on dynamic simulation using Smooth Particle Hydrodynamics (SPH) modelling considering dilatancy effects. As shown in the Fig. 4, the most obvious feature of the landslide was that its travelling distance exceeded 1.2 km and the landslide mobility index equal to 0.092 was much lower than that of a general landslide. A landslide mobility index lower than 0.3 denotes high mobility. The Dilatancy model describes the interaction between the fluid and solid phases. The key role of these dilatancy models is the combination of the dilation and contraction behaviours with the equilibrium solid volume fraction, which is related to the solid volume fraction and effective stress. The grid or mesh-based methods have been widely applied in various areas of computational fluid dynamics and computational solid mechanics (Anderson & Wendt 1995, Fung & Tong 2001).

However, the existence of the grid or mesh can cause various difficulties in solving problems related to the free surface, extremely large deformations, a deformable boundary, and a moving interface (Liu & Liu 2010). Mesh-free methods have been developed in the recent past (Liu & Gu 2005), and SPH methods, which were invented to solve astrophysical problems, have been widely applied in many fields (Lucy 1977, Liu & Liu 2003, Violeau 2012). The soil on the sliding surface was liquefied (Ouyang et al. 2016), and the bottom of the deposited body exerted excess pore water pressure.

Udapalatha Municipal Landfill at Udapalatha, Sri Lanka

Prathapan et al. (2015) carried out the modelling of Udapalatha Municipal landfill (Sri Lanka) to discuss the spatial variation of shear strength and consolidation characteristics. Chances of slope failure of a landfill can

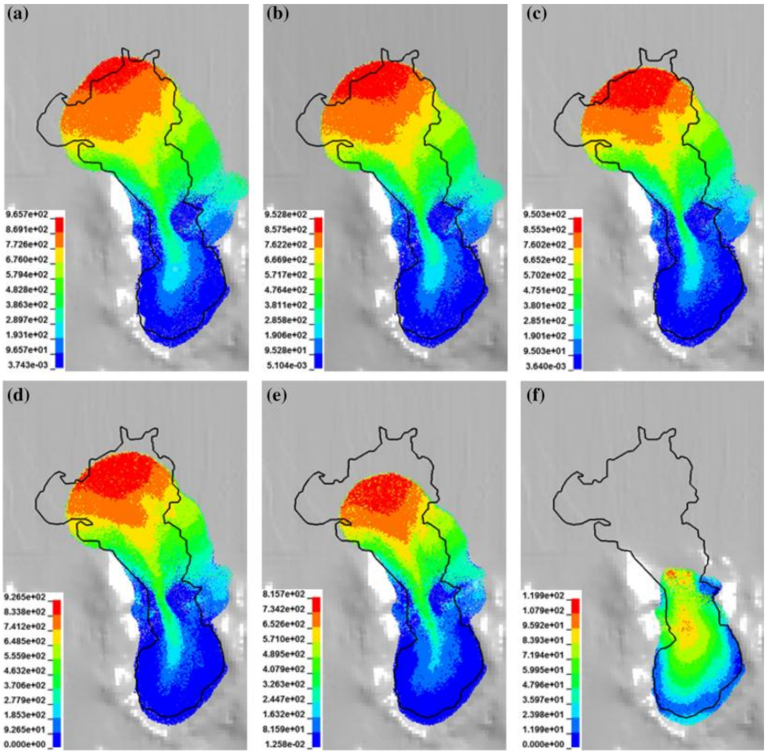


Fig. 4: Modelling output in terms of deposition area and displacements of different solid volume fractions at t = 200s for (a) $m_0 = 0.57$; (b) $m_0 = 0.59$; (c) $m_0 = 0.61$; (d) $m_0 = 0.62$; (e) $m_0 = 0.63$; and (f) $m_0 = 0.64$ (Liang et al. 2019).

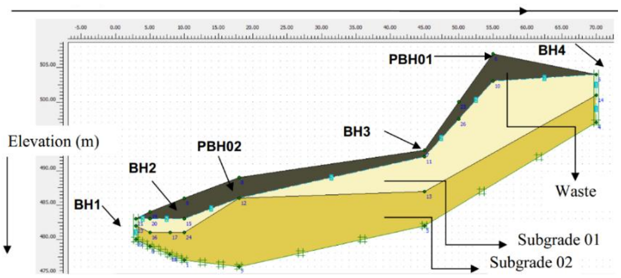


Fig. 5: Modelling of Cross-section of new site and locations of boreholes.

Table 2: Shear strength and consolidation parameters (Prathapan et al. 2015).

Location	Shear strength parameters		Consolidation parameters	
	c′ (kPa)	φ′ (degree)	κ*	λ*
BH 02	46.7	19.8	0.0020	0.0616
PBH 02	50.2	14.0	0.0021	0.0707
PBH 01	15.4	31.8	0.0056	0.0790

occur during the construction of the landfill or after the closure of the landfill.

The shear strength and consolidation were determined using direct shear and Oedometer tests. Stability is measured in terms of the factors of safety, which can be evaluated using SLOPE/W and PLAXIS 2D software considering both homogeneities as well as the heterogeneity of the material properties. The above analysis yielded critical factors of safety ranging between 1.18 and 1.72 in Slope/W and 1.14 and 1.43 in PLAXIS 2D when heterogeneous properties were used in separate analyses assuming homogeneity (Fig. 5). However, by considering spatial variation, the factor of safety was found to be 1.62 and 1.32 in SLOPE/W and PLAXIS 2D analyses respectively, emphasizing the importance of considering the spatial variation of shear strength properties in stability analyses.

The parameters for PLAXIS 2D analysis are effective cohesion (c′), effective friction angle (φ′), modified compression index (λ*), modified swelling index (κ*), modified creep index (μ*) and unit weight (γ). While, on another hand, the input parameters for SLOPE/W software are effective cohesion (c′), effective friction angle (φ′) and unit weight (γ). Results for both the direct shear test and consolidation shear test at three different locations are given in Table 2. Cross-section of the landfill modelled by both PLAXIS 2D and SLOPE/W for calculating the Factor of Safety (FOS) which is shown in the Figs. 6 & 7. The estimated value of FOS using both the methods is also mentioned in Table 3.

Based on the analyses carried out considering uniform as well as spatial variations of properties, the following conclusions are made.

(a) Both shear strength, as well as consolidation parameters, showed considerable variation within the landfill.

(b) The range of values of FOS obtained corresponding to the uniform variation of lowest and highest values of effective cohesion were significant.

Table 3: Summary of the factor of safety values (Prathapan et al. 2015).

Analysis Method		Cohesion (kPa)	Friction Angle (degree)	Factor of Safety	
				SLOPE/W	PALXIS 2D
Spatial Variation	-	-	-	1.618	1.319
Uniform	PBH 01	15.4	31.8	1.184	1.139
	BH 02	46.7	19.8	1.594	1.382
	PBH 02	50.2	14.0	1.722	1.428

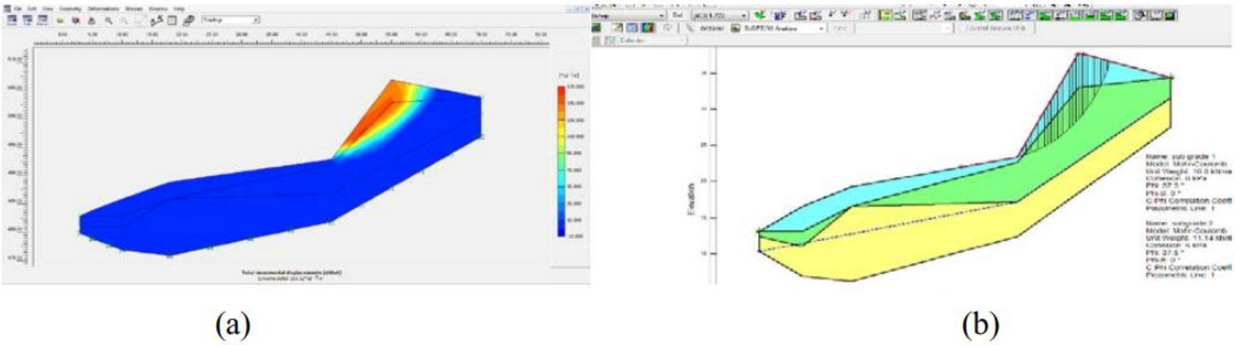
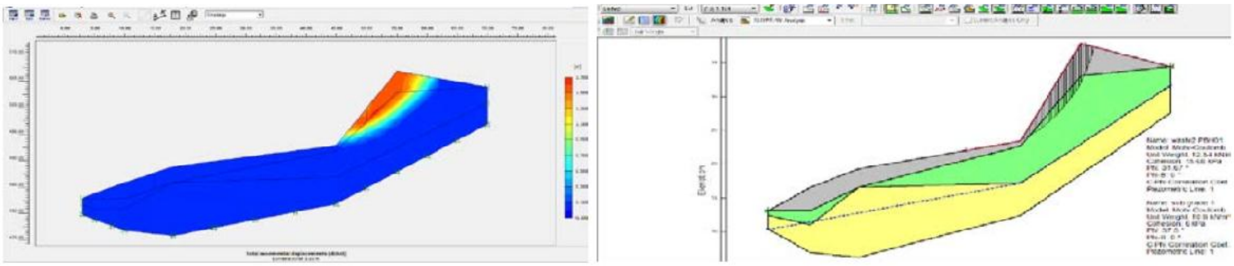

(a) (b)

Fig. 6: Critical failure surfaces obtained from (a) PLAXIS 2D and (b) SLOPE/W analyses using a higher value of cohesion obtained from PBH02.



(a) (b)

Fig. 7: Critical failure surfaces obtained from (a) PLAXIS 2D and (b) SLOPE/W analyses using a lower value of cohesion obtained from PBH01.

(c) The existing landfill is found to be stable considering the spatial variation of shear strength properties.

CONCLUSION

Expansion of waste generation, economy and rapid population growth in particularly among developing nations increased the landfill demands. Inferable from money related limitations, landfills built as a rule endured with the absence of natural reduction measures, for example, leachate assortment frameworks and coating materials. Subsequently, a lot of contamination is incurred upon the environment. It is likewise accepted that weak layers in the landfill brought about via occasional or different elements, or inadequately compacted soil spread layers may have added to the failures. The most significant conclusion is that proprietors and administrators of landfills, be they dump or built, structured landfills should utilize prepared and skilled enough to work their landfills. The administrative or controlling specialists ought to likewise be prepared and proficient. Measures for controlling and expanding ability ought to be presented, if not present. The disposal of MSW by uncompacted revealed end-tipped dumping ought to be eliminated at the earliest opportunity. Where impractical, steeps, hilly regions and especially sites crossed by streams or other watercourses, or situated in marshes or lakes should be avoided.

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