Static and Seismic Stability Analysis of Malaysia's Largest Sanitary Landfill

Hamed Saiedi
Department of Civil Engineering – University of Calgary, Calgary, Alberta, Canada
Saied Saiedi, Niraku Rosmawati Binti Ahmad
Department of Civil Engineering – Petronas University of Technology, Tronoh, Ipoh, Malaysia
Ho Kum Hou
Tai Hoe Resources Sdn Bhd, Kuala Lumpur, Selangor, Malaysia

ABSTRACT
The global static and seismic stability of the first phase of the largest Malaysian Sanitary Landfill in Bukit Tagar is investigated and the sensitivity of the safety factor to the waste geotechnical parameters is demonstrated. It is found that with satisfactory drainage conditions, the landfill is stable under the range of possible values of the waste's geotechnical parameters. The landfill is not stable under a hypothetical failed drainage and extreme rainfall and proper drainage can assure satisfactory performance during earthquakes.

RÉSUMÉ
La stabilité globale statiques et sismiques de la première phase de la plus grande d'enfouissement sanitaire de Malaisie à Bukit Tagar est étudiée et la sensibilité du coefficient de sécurité pour les déchets des paramètres géotechniques est démontrée. Il est constaté que, avec un bon drainage, la mise en décharge est stable dans la gamme des valeurs possibles des paramètres géotechniques des déchets. La mise en décharge n'est pas stable dans un drainage hypothétique échoué et les précipitations extrêmes et le drainage peuvent assurer une performance satisfaisante au cours de tremblements de terre.

1 INTRODUCTION

Malaysia generates 18,000 tonnes of solid waste daily, of which 5,500 tonnes come from Klang Valley with 8 million people out of the total population of 26 million. Landfills have for long been the primary system for waste disposal in Malaysia and are to remain as such for the foreseeable future. Out of 177 landfills built by 1997, 90 were open dumpsites, 76 were controlled landfills, and 11 were sanitary landfills. Moving towards a modern era of building environmentally-friendly sanitary landfills, Malaysia closed 60 environmentally-hostile landfills by 2001 and planned to close 16 critical dumpsites near water intakes in 2007 (Agamuthu 2007, MHLG 1999).

The objectives of the paper are to investigate the static and seismic stability of the first landfill of the largest Malaysian sanitary landfill site and to get insight into the sensitivity of the safety factor to geotechnical parameters of the waste as well as to the water level conditions.

2 BUKIT TAGAR LANDFILL

The largest sanitary landfill in operation in Malaysia is Bukit Tagar Sanitary Landfill in Hulu Selangor, 50 km north of Kuala Lumpur. The climate is tropical characterized by an average annual rainfall of 2.8 m. The overall rainfall occurs consistently throughout the year. However, there are four months of higher than average rainfall. Bukit Tagar landfill started operating in April 2005 and is now serving a population of 8 million in Kuala Lumpur City and Klang Valley. It receives an average of 2000 ton/day of waste (Kortegast *et al.* 2007). With a potential capacity of 120 million tonnes on an 800-ha-land, it is expected to operate for 40 years. It is designed to receive a mix of non-hazardous commercial and domestic putrescible and inert waste. Waste disposal consists of compaction before transportation to the landfill, repeated compaction of the dumped waste on site, and application of daily soil cover at the end of each working day. This soil cover is then removed from the waste surface the following day for continued disposal. Construction of the first phase of Bukit Tagar landfill, the 'Advance Phase' (referred to as BTL for simplicity in this paper), began in 2004. The waste was disposed of from April 2005 till November 2007. As of April 2008, its closure works (consisting of cover soil and lining installation) have been completed. BTL is built adjacent to a hill from one side. The landfill incorporates a full protective liner at the landfill base (comprised of compacted soil, geomembrane, geo-textile and a geo-cushion). Leachate collection pipes have been placed around the base, draining water to a nearby leachate pond before being pumped to a leachate treatment plant.

BTL has an area close to 4 ha with a capacity close to 3.5 million tonnes of waste. It is a diamond-shaped landfill with a maximum length of 270 m, a width of 340 m and a height of 50 m from the base to top. The typical base side slopes are 2.5H:1V with side lengths of 41 m. A 9-m-wide berm connects the slopes. Examining the geometry of the landfill at various sections, a critical cross-section is identified with a large length and small protecting toe berm. Figure 1 depicts the geometry of this section with which all stability analyses of the present paper are performed. The landfill consultants have designed BTL as a USEPA level 4 sanitary landfill (Tonkin and Taylor Group 2010).

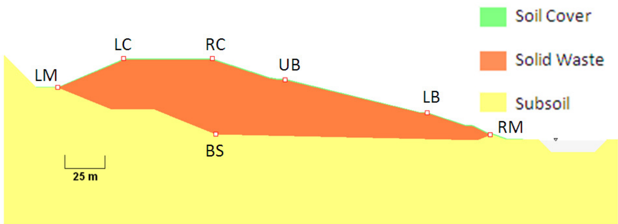

Figure 1. Cross-section of the Advance Phase of Bukit Tagar Landfill

3 STABILITY OF LANDFILLS

Landfill stability can be analysed in three ways: global stability (dealing with the total landfill mass), liner slope stability and cover soil slope stability; each of which should be performed under static and seismic conditions In the analysis, the stability is ensured if the factor of safety FS, (defined as the ratio of resistive force to the active sliding force) is greater than prescribed values given by proper standards.

Failures in landfill stability can be related to six main categories (Xuede *et al.* 2005): 1. Leachate collection system. 2. Final cover system. 3. Soil slope, toe, or base. 4. Foundation failure through subsoil, liner and waste. 5. Failure within waste mass. 6. Translational failure along liner system at base and up through waste or liner. Out of a comprehensive study into sustainability of Bukit Tagar landfill as the largest Malaysian sanitary landfill, the present paper reports only the global seismic analysis of the post-closure conditions pertaining to items 3 to 5 of the above-mentioned list.

Typical regulatory FS values are 1.3 for waste disposal stage and 1.5 for both pre-waste disposal and post-closure stages for landfills in the static stage and 1.0 for seismic design (USEPA 1993; Isenberg 2003).

In the seismic analysis, employing numerical procedures such as Finite Elements Methods, distributions of stresses and deformations are sought. Of particular interest are deformations and displacements, local cracks in the various components and broken collection pipes. To allow for proper design of landfills for earthquakes, limiting values on the permanent displacements of various landfill components are set forth (Table 1).

Table 1. Generic Allowable Seismic Displacements for Municipal Solid Waste Landfills (Kavazanjian 1999)

Component	Allowable Displacement
Liner System	150 to 300 mm
Cover System	300 mm to 1 m
Waste Mass	1 m
Roadways, Embankments	1 m
Surface Water Controls	1 m
Gas Collection System	No Limit

4 EXAMPLES OF LANDFILL STABILITY FAILURES

Koerner and Soong (2000) reported their analysis of the failure of ten large solid waste landfills in various countries. They concluded that the triggering mechanism of failure was one of three liquid-related factors: leachate build-up within the waste mass, wet clay beneath the geomembrane, and excessively wet foundation soil.

Two disastrous landfill failures occurred in the last 10 years in South East Asia: Leuwigajah dumpsite (Indonesia) and Payatas landfill (the Philippines). Koelsh *et al.* (2007) described and analyzed the failure at the Leuwigajah dumpsite in Indonesia in 2005 whereby 2.7×106 m3 of waste slid and killed 147 people. The stability analysis suggested that both water pressure in the subsoil and a severely damaged reinforcement (due to smouldering landfill fire) triggered the failure. Merry *et al.* (2005) documented and briefly analyzed the failure of a rapidly moving slope in Payatas Landfill in the Philippines in 2000, where 1.2 ×106 m3 of municipal sanitary waste (MSW) went downhill, killing at least 230 people. Two typhoons, bringing a total precipitation of 0.75 m in ten days, preceded the failure. They attributed the failure to elevated pore pressures, caused by the build-up of landfill gas unable to escape the highly saturated waste. The tropical climatic conditions in Malaysia are similar to the South-East Asian countries reported above. The countries in the region increasingly build larger and higher landfills making it necessary to investigate the stability of landfills in Malaysia, where the annual precipitation is even larger.

The observed performance of solid waste landfills during recent earthquakes has been encouraging in that no global instability has occurred. However, significant damage in the form of geomembrane tears, cover cracking, broken gas header lines, and loss of power to gas extraction systems was experienced at several landfills during the 1994 Northridge earthquake. Cover systems in landfills have been specifically vulnerable to recent earthquakes (Maugeri and Sêco e Pinto 2005). Kavazanjian (1999) cites that a lined landfill subjected to ground accelerations larger than 0.3 g suffered significant damages, but without harmful discharge of contaminants.

5 STATIC STABILITY OF BTL

5.1 Static Stability Parameters of BTL

The geotechnical parameters of interest in stability analysis are the shear strength parameters (cohesion c and friction angle φ) and unit weight γ for the subsoil, waste and cover soil. In the absence of access to design values adopted in the original design and to testing on the actual waste, shear strength parameters for MSW of BTL were taken as $\varphi = 28°$ and c = 19 kPa. These values, taken as the same values used in stability analysis of Payatas landfill in the Philippines by Merry *et al.* (2005) are substantiated by the following three arguments: (a) KL waste resembles that of the Philippines in composition, as can be seen in Table 2 (adopted from Sivapalan *et al.* 2004; Hoornweg and Verma 1999). (b) These values correspond well with the compiled shear strength parameters for MSW from Singh and Murphy (1990), Zekkos (2005) and Xuede *et al.* (2001) (Saiedi *et al.* 2008a). (c) This data compares well with that from other tropical countries and from bioreactor (wet MSW) landfills (Merry *et al.* 2005).

A unit weight of γ=10.2 kN/m3 was taken for the MSW of BTL. This is the same as that in Payatas landfill, in the Philippines, mentioned earlier. Given the fact that BTL is located in a region with high annual precipitation (implying a wetter MSW), this estimate is close to the range of 8.8-10.2 kN/m3 recommended by Kavazanjian et al. (1995).

Table 2. Composition (in %) of MSW in South East Asia

Component	Kuala Lumpur	Philippines
Compostable	41	41
Paper	18	19
Plastic	20	14
Glass	4	3
Metal	3	5
Others	14	18

For the Subsoil, samples were taken from BTL subsoil yielding the test results of φ=28°, c=5 kPa and γ=17.6 kN/m^3 assumed to exist homogenously.

As for the hydrological conditions, Kortegast *et al.* (2007) discussed leachate generation from BTL based on field measurement supplemented by the application of HELP software (WES 1994). The study showed that the range of 90-160 m^3/d (with a peak of 180) for leachate generation anticipated in the preliminary design assessment was off by about 350%. They found that a range of 325-550 m^3/d (with a peak of 1150) was closer to the actual experience. Average base flow was at 17% of the waste weight. Close to 20% of the leachate generation was attributed to the flow of clean surface water from up-gradient formation slopes to the waste mass. They suggested that diverting stormwater away from the landfill, minimization of the working face, timely and appropriate use of daily and intermediate cover soils, and avoiding semi-aerobic landfilling were necessary for minimization of leachate generation.

5.2 Trial Ranges of the Main Parameters

To provide for an insight into the sensitivity to the main parameters, a range of values were tried in the stability analysis of the landfill. The trial values are: c1=10, c2=19, c3=28 kPa; φ1=20°, φ2=28°, φ3=36°; γ1=13.9, γ2=10.2, γ3=6.5 kN/m^3. Three middle values (i.e. c2=19 kPa, φ2=28°, γ2=19 kN/m^3) are considered realistic estimates as opposed to the worst case (i.e. c1=10 kPa, φ1=20°, γ3=6.5 kN/m^3) and best case (i.e. c3=28 kPa, φ3=36°, γ1=13.9 kN/m^3) waste parameter scenarios.

Four water level (WL) conditions in the landfill are attempted. WL0: Dry landfill that corresponds to an ideal situation of perfect drainage and little rainfall. WL1: Low WL in the landfill that corresponds to a significant flow of infiltrated precipitation and leachate from 'formation slope' to the toe under moderate precipitation. WL2: Intermediate WL in the landfill that corresponds to a low flow of infiltrated precipitation and leachate from 'formation slope' to the toe. This is associated with poor performance of drainage system under heavy rainfalls. WL3: High WL in the landfill that corresponds to extreme storms with poor performance of drainage system and top liner system. These four conditions, shown in Figure 4, move from best case to worst case scenarios for the drainage and precipitation.

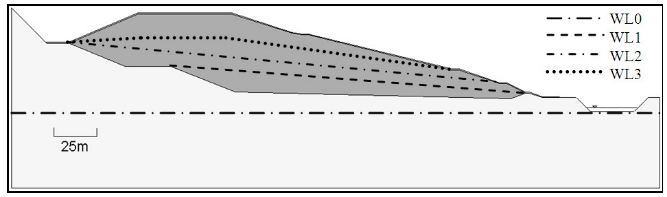

Figure 2. Water level scenarios used for simulations

5.3 Global Stability Analysis and Assumptions

The following gives the assumptions and methods involved in the static stability analysis of BTL (the 'Advance Phase' of Bukit Tagar landfill) as practiced in the present research: 1. The 2-D section in Figure 1 represents the landfill. This is a conservative assumption (Koerner and Soong 2000). 2. The role of liners (base and top) on the global stability is negligible (Koerner 2007). 3. The Morgenstern-Price Method (Morgenstern and Price 1965) for stability analysis is used. This is a limit equilibrium method employing an arbitrary mathematical function to describe the direction of the inter-slice forces. 4. The full version of the commercial software Slope/W (Geo-Slope International Ltd 2007) is utilised for the global stability analysis in this paper.

6 SEISMIC STABILITY OF BTL

6.1 Seismic Stability Parameters of BTL

For the seismic analysis of BTL, the mid-range of the waste parameters of the trial range described in section 5.2 are used, i.e. c2=19 kPa, φ2=28° and γ2=10.2 kN/m3. The dynamic shear modulus, G, was taken from Sharma and Goyal (1991) as 28.9 MPa for Municipal Refuse. Zekkos (2005) has reported a range of variation of Poisson's ratio for MSW of 0.3 to 0.5 and specifically, 0.3 to 0.35 for MSW with no fibrous materials. Since Malaysian waste is primarily non-fibrous in nature (Table 1), the Poisson's ratio of Malaysian MSW was taken as the median of the range of variation of υ, equal to 0.3. MSW damping ratio is a function of shear strain (Zekkos 2005). For shear strains of 0.0001% and 1%, MSW's damping ratio varies from 1% to 25%. A constant damping ratio was required for modeling using the Quake/W (Geo-Slope International Ltd 2007) program used for the analysis and so a value of 10% was chosen.

The sampled subsoil was determined to be hard clay, which is abundantly found in Malaysia. The dynamic properties of the subsoil were determined by utilizing data in the literature on stiff clays. The shear modulus was approximated to be equal to that of medium clay, which varies between 13.6-27.6 MPa (Bowles 1997). A value of 21 MPa was used to represent the BTL subsoil. A Poisson's ratio of 0.38, closer to the Poisson's ratio range of 0.4-0.5, reported for saturated clays by Bowles (1997), was used. A damping ratio of 5% for the subsoil clay was taken which matches the values in the literature reported by Bowles (1997).

Two water level (WL) conditions in the landfill are attempted: WL0 and WL1 as shown in Figure 2. These two conditions shall sufficiently represent practical water levels in the landfill considering that extreme precipitations are unlikely to occur simultaneously with an extreme earthquake event with a return period of 100 years.

6.2 Global Stability Analysis and Assumptions

One-dimensional stability analysis can cause under-predictions of the seismic response of landfills (Rathje and Bray 1999). 2-D analysis is more conservative than 3-D analysis for static stability analysis (Koerner and Soong 2000). For the purposes of this paper, 2-D analysis is seen as adequate. In the present paper, equivalent linear dynamic analysis using the QUAKE/W module of GeoStudio software (Geo-Slope International Ltd 2007) was employed.

An amplification of the time-history of the North-South component of the El-Centro earthquake on 19th of May, 1940 as recorded at Imperial Valley, California was employed in this paper to obtain the design earthquake. The amplification factor had to be representative of the maximum likely earthquake to occur in Malaysia during 100 years. A frequency analysis of earthquakes of various magnitudes was carried out as reported in Saiedi *et al.* (2008b), from which an amplification factor of 1.125 times the El-Centro earthquake was seen as adequate as a design earthquake with a return period of 100 years. This resulted in the peak acceleration of the El Centro earthquake becoming 0.394g from 0.35g.

In addition, Mauger and Sêco e Pinto (2005) have stated that in the case of landfills resting on soft clay or alluvial soil, the site amplification effect must be taken into consideration to select a design earthquake. Although the results of sampling of the subsoil at BTL indicated an abundance of hard clay at the site, for conservatism, the effect of wave propagation by the landfill waste, was incorporated by using Figure 3. For the refuse, a peak acceleration of 0.394g at the base corresponds to peak acceleration at the crest of 0.52g. To account for this amplification which gradually increases in the waste mass from the base to the crest, a value of 0.457g, the mean of the base and crest accelerations, was taken to apply to the subsoil and the entire landfill profile (shown in Figure 1). The resulting time-history, shown in Figure 4, was used for the analysis.

The following describes the assumptions and methods involved in the seismic stability analysis of BTL as practiced in the present research. 1. The 2-D section in Figure 1 represents the landfill. This is a conservative assumption (Koerner and Soong 2000). 2. Side and bottom boundaries of the analysis cross-section were respectively assumed to be fixed in the vertical and both 2-D directions. 3. The role of liners (base and top) on the global stability is negligible (Koerner 2007). 4. Finite Element analysis was used to determine the initial static stresses in the landfill using QUAKE/W. 5. Equivalent Linear Dynamic analyses followed by the Newmark Sliding Block Analyses (Newmark 1965) were utilized for assessment of the seismic stability of the landfill. 6. Factors of safety were calculated using the Morgernstern-Price Method (Morgenstern and Price 1965). 7. Two modules of commercial software GeoStudio 2007 (Geo-Slope International Ltd 2007), QUAKE/W and SLOPE/W are utilised for the global seismic stability analysis in this paper.

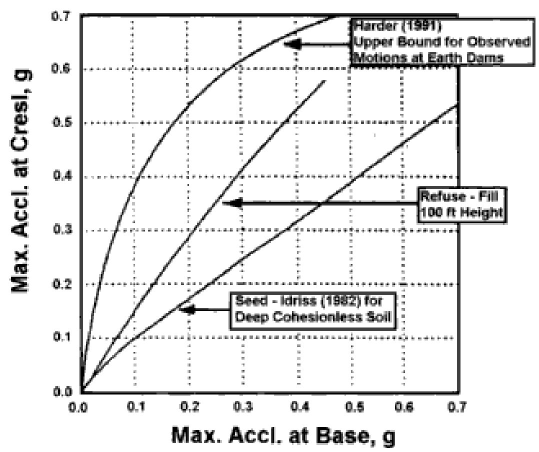

Figure 3. Amplification of acceleration by earth dams and waste landfills (Singh and Sun 1995)

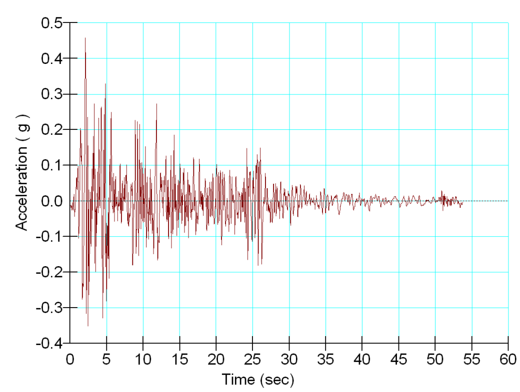

Figure 4. Modified time-history of El Centro earthquake used for seismic analysis

7 RESULTS AND DISCUSSIONS

7.1 Results of Static Analysis

Given four scenarios for WL and three values for each of c, φ and γ, a total number of 108 runs were systematically performed. Table 2 contains the resulting safety factors (FS) for all simulations.

Table 2. Resultant Factors of Safety from All Simulations

WL \ γ		γ1			γ2			γ3		
		φ1	φ2	φ3	φ1	φ2	φ3	φ1	φ2	φ3
0	c1	**1.84**	2.50	2.85	1.92	2.64	3.11	2.08	2.81	3.38
	c2	2.05	2.61	2.98	2.20	**2.79**	3.25	2.50	3.14	3.61
	c3	2.26	2.72	3.07	2.48	2.94	3.36	2.93	3.36	**3.83**
1	c1	**1.68**	1.86	1.96	1.73	2.01	2.19	1.77	2.09	2.39
	c2	1.77	1.93	2.03	1.85	**2.12**	2.26	1.99	2.26	2.50
	c3	1.85	2.00	2.10	1.96	2.19	2.30	2.17	2.42	**2.59**
2	c1	1.37	1.48	1.59	1.36	1.53	1.63	**0.99**	1.06	1.15
	c2	1.50	1.60	1.72	1.53	**1.70**	1.79	1.38	1.50	1.63
	c3	1.62	1.73	1.83	1.65	1.83	**1.94**	1.59	1.71	1.84
3	c1	1.05	1.25	1.32	0.86	1.00	1.07	**0.32**	0.29	0.34
	c2	1.20	1.37	1.44	1.04	**1.13**	1.20	0.45	0.64	0.53
	c3	1.31	1.45	**1.51**	1.18	1.26	1.33	0.65	0.64	0.65

Note: Shaded cells show the min, realistic & max FS in each WL case

The FS values were then plotted versus appropriate parameters. FS=1.5 represents the border line below which the landfill is considered unsafe. Figure 5 depicts FS versus WL conditions for three distinct scenarios defined in section 5.2. The figure indicates the following. (i) The landfill is stable with WL0 and WL1 for all three scenarios. (ii) In the realistic scenario, the landfill is safe unless with the poorest drainage condition and extreme precipitation (WL3). (iii) Under the best case scenario, the landfill is safe. The effect of the unit weight (i.e., compaction) on the overall stability of the landfill is depicted in Figure 6. With high water levels (e.g, WL3), lower unit weights (poor compaction) poses more risk to the stability. Hence, the significance of compaction increases when there is a risk of poor drainage and large durable precipitations. Figure 7 shows the impacts of c, φ and WL on the safety factor for a constant γ=10.2 kN/m^3. A close look at the results indicate that the WL dominates other factors, except for the ideal drainage condition (WL0) where FS is significantly sensitive to variation of c and φ. For the dry landfill, φ has a more significant role than c.

The impacts of unit weight, friction angle and WL on the FS for a constant c=19 kPa were also investigated. The results (not shown here) suggest that FS is highly sensitive to φ for drained conditions at the chosen range of γ. Additionally, the data indicated that as WL increases dramatically, the best compaction brings much more stability.

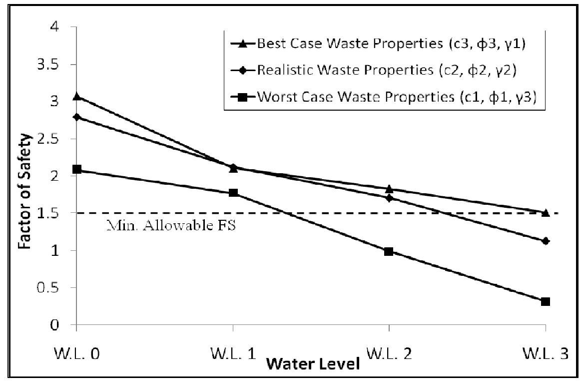

Figure 5. Safety factor for four water level scenarios

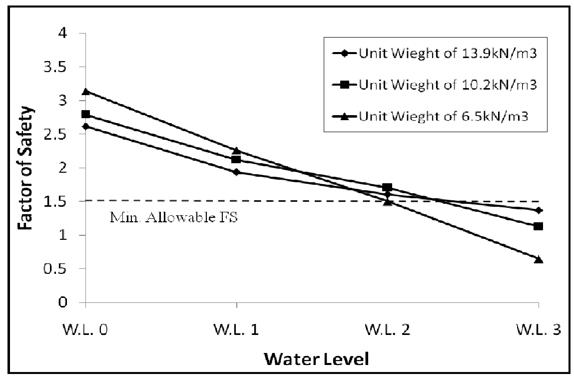

Figure 6. The impact of unit weight and WL on the safety factor

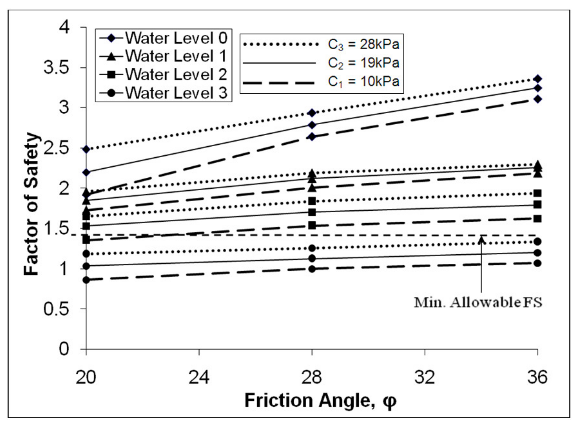

Figure 7. Safety factor versus φ and c for γ = 10.2kN/m^3

Of particular practical significance are the maximum and minimum FS values for each WL scenario. These are highlighted in Table 2.

1. For the ideal drained landfill (WL0), FS_{max}= 3.83 and FS_{min}= 1.84. These imply perfect global stability of Bukit Tagar landfill.

2. For the good drainage condition (WL1), FS_{max}= 2.59 and FS_{min}= 1.68. These indicate reasonable global stability of the landfill.

3. For the poor drainage condition under heavy rainfall (WL2), FS_{max}= 1.94 and FS_{min}= 0.99. It should be noted that for the realistic parameters values, FS=1.7 implies acceptable safety. However, FS_{min}= 0.99 that corresponds to the worst case scenario (i.e, c1=10, φ1=20°, γ1=6.5) pronounces the importance of the drainage.

4. For the poorest drainage condition associated with extreme precipitation (WL3), FS_{max}= 1.51 and FS_{min}= 0.32. This highlights the vitality of sufficient drainage during consistent intense rainfalls usually occurring in the monsoon season.

The above points on the adequate drainage are signified in the light of the findings of another study on the leachate generation of the BTL (Kortegast *et al.* 2007) in which the authors report an actual leachate discharge that was 3.5 times the anticipated flow.

7.2 Results of Seismic Analysis

When the landfill was at WL0, the resulting graph of Factor of Safety vs. time was as in Figure 8.

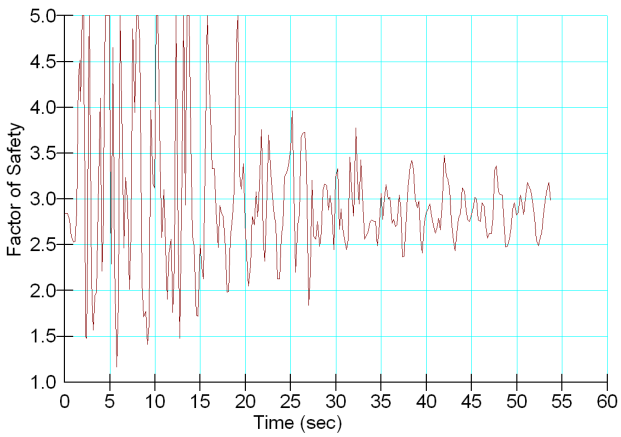

Figure 8. Variation of Factor of Safety with Time for WL0 when subject to the design earthquake

Figure 8 shows that the FS reaches a minimum of 1.167 at second 5.47 during the shaking. This minimum value is more than the USEPA requirement of 1.0 and thus, is acceptable. The figure is yet quite low and can be rather worrying. It is observed that the FS starts from 2.79 and experiences greatly varying FS values especially in the first 15 seconds of shaking. This implies the high relative displacements the landfill goes through at the beginning of the shaking (i.e. the landfill leans backwards and forwards with respect to a fixed datum). In accordance to the Newmark Sliding Block analysis, since the FS value is consistently above 1.0, the yield acceleration has not been reached and no permanent deformations will occur.

Furthermore, analysis on the effect of the design earthquake when the landfill is at WL1 was done. Figure 9 is the plot of variation of FS vs. time when the water level is at WL1 and pore water pressure conditions exist within the wet waste mass. The graph shows that the FS approaches very near to the seismic stability requirement of 1.0. The exact value given by the software is 1.014. Such a critical FS can be alarming due to the fact that increasing water levels may threaten the stability of the landfill. It should be noted however that as the FS is consistently higher than 1.0, permanent displacements do not occur at WL1 either. This means the landfill has satisfied the criteria of the minimum allowable displacement of 1m for the waste mass (see Table 1). Some stability assurance can be found in this light. However, the criticality of the seismic stability of the landfill at WL1 must be realized.

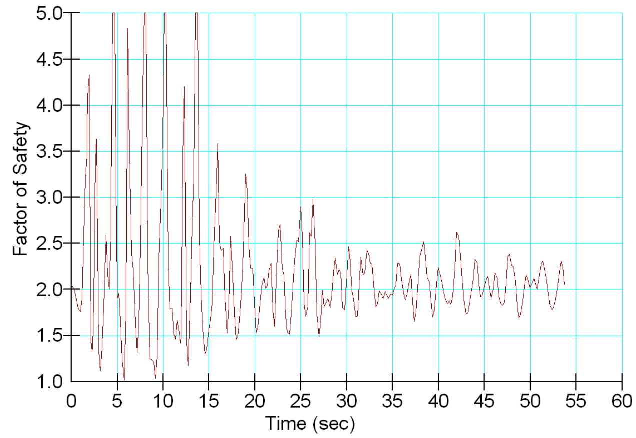

Figure 9. Variation of Factor of Safety with Time for WL1 when subject to the design earthquake

It must be noted that the equivalent-linear dynamic analysis usually gives results that are too conservative. Additionally, the design earthquake used for analysis had assumed an average peak acceleration of 0.457g to be applied to the entire analysis cross-section (including a large portion of the subsoil). This is while the subsoil is expected to be entirely subjected to the outcrop acceleration (i.e. the max. acceleration at the base of 0.394g). Much conservatism is inherent in these assumptions.

8 CONCLUSIONS

8.1 Conclusions of Static Analysis

The global static stability of the 'Advance Phase' of Bukit Tagar landfill, Malaysia, is analysed with a wide range of parameters for friction angle φ, cohesion c, unit weight γ, and water level (WL). More than 100 computer simulations were performed leading to the following findings: 1. A water level that is lowered (less than 12 m above the base) by an efficient drainage system will guarantee reliable stability under the full range of possible values for φ, c, and γ of the disposed waste (see Figure 5). 2. With poor drainage, more likely under heavy precipitation, sufficient compaction becomes more crucial (see Figure 6). 3. Safety factor (FS) is dominated by water level (WL) to a much greater extent compared to c and φ. 4. With WL increasing in poor drainage conditions or under heavy precipitation (WL2), a sufficient FS can only be obtained if the waste is well compacted (γ1 and γ2). This does not hold true with WL3 that implies extreme rainfall and failed drainage (see Figure 6).

Large FS values in a great majority of stability simulations of the 'Advance Phase' of Bukit Tagar landfill indicate an adequate design and implementation of the landfill. The inadequacy of the landfill under a hypothetical failed drainage and extreme rainfall is in line with the frequent observation that most failures of large municipal landfills are triggered by water-related factors. To ensure proper drainage at landfill sites, it is recommended that conventional standpipes and air piezometers be installed in the landfills to help monitor water levels, as well as to determine the landfill's safety factor more reliably.

8.2 Conclusions of Seismic Analysis

The global seismic stability of the 'Advance Phase' of the Bukit Tagar landfill, Malaysia, is analyzed under a design earthquake of a return period of 100 years, obtained by means of frequency analysis, for two water level conditions. Amplification of the acceleration of the landfills is taken into consideration. Equivalent-linear dynamic analysis of the landfill was supplemented by the Newmark Sliding Block method of analysis to obtain variations of FS with time for the duration of the earthquake. The significant results of the paper are as follows: 1. The BTL with a water level at WL0 is sufficiently stable against a Malaysian design earthquake of a return period of 100 years and no permanent deformation was calculated to occur then. 2. The BTL with a water level at WL1 is also sufficiently, yet critically, stable against a Malaysian design earthquake of a return period of 100 years and no permanent deformation was calculated to occur. 3. Given the critical FS values when the landfill is subject to WL1, it is highlighted that proper and sufficient drainage are most essential at the site to prevent stability failures in the case of extreme earthquake events.

REFERENCES

Agamuthu P. 2007. Post-closure of landfills: issues and policy, *Waste Management Research*.

Bowles J.E. 1997. *Foundation Analysis and Design*, McGraw Hill, New York, NY, USA.

Geo-Slope International Ltd 2007. *Slope/W software and manual*, second edition, Calgary, Canada.

Hoornweg D.L.T. and Verma K. 1999. What a Waste - Solid Waste Management in Asia, World Bank, Urban Development Sector Unit, East Asia and Pacific Region.

Isenberg, R.H. 2003. Landfill and Waste Geotechnical Stability, *USEPA Bioreactor Workshop*, Reston, Virginia, USA, 27 February 2003.

Kavazanjian E. Jr., Matasovic N., Bonaparte R., Schmertmann G.R. 1995. Evaluation of MSW properties for seismic analysis, Geoenvironment 2000, *ASCE Geotechnical Special Publication #46*, V.2, pp. 126-141.

Kavazanjian E. K. Jr. 1999. Seismic Design of Solid Waste Containment Facilities, Proceedings of the 8th Canadian Conference on Earthquake Engineering, Vancouver, Canada, June 1999, pp. 51-89.

Koelsch, F., Fricke, K., Mahler, C., Damanhuri E. 2005. Stability of landfills – The Bandung disaster, Proc. of the 10th Intl. Landfill Symposium, Cagliari, Italy.

Koerner R.M. 2007. Personal e-mail communication with the second author, December 2007.

Koerner R.M. and Soong T.Y. 2000. Stability Assessment of Ten Large Landfill Failures. Advances in Transportation and Geoenvironmental Systems Using Geosynthetics, Proc. of Sessions of GeoDenver 2000, *ASCE Geotechnical Special Publication No. 103*.

Kortegast A.P., Eldridge S.F., Richards B.A., Yong S., Chock E.T., Bryce A., Robinson H., Carville M. 2007. Leachate generation and treatment at the Bukit Tagar landfill, Malaysia, Sardinia 2007, 11th International Waste Management and Landfill Symposium, S Margherita di Pula, Sardinia, Italy, 1-5 October.

Maugeri M. and Sêco e Pinto P.S. 2005. Seismic Design of Solid Waste Landfills and Lining Systems, *International Technical Committee (ITC5) on Environmental Geotechnics Report No. 5*, ISSMGE, Chapter 5, September 2005.

Merry S.M., Kavazanjian E., Fritz W.U. 2005. Reconnaissance of the July 10, 2000, Payatas Landfill Failure", *Journal of Performance of Constructed Facilities*, Vol. 19, No. 2, May 2005, pp. 100-107.

MHLG (Ministry of Housing and Local Government, Malaysia) 1999. Solid waste management factsheet at local authorities areas, MHLG, 1, 5-6.

Morgenstern N. R. and Price V. E. 1965. The analysis of the stability of general slip surfaces, *Géotechnique* 15(1): 79-93.

Newmark, N. 1965. Effects of earthquakes on dams and embankments, *Geotechnique*, 15(2): 139-160.

Rathje E. M. and Bray J. D. 1999. Two Dimensional Seismic Response of Solid-Waste Landfills, Proc. of 2nd Inter. Conf. On Earthquake Geotechnical Engineering, ISSMFE, Seco e Pinto, ed., Balkema, Lisbon, Portugal, Vol. 2, pp. 655-660, June 21-25, 1999.

Saiedi H., Saiedi S., Rosmawati N., Hou H.K. 2008a. Static Stability Analysis of the Largest Malaysian Sanitary Landfill, International Conference on Geotechnical and Highway Engineering, Geotropika 2008, Kuala Lumpur, May 26-27, 2008.

Saiedi H., Saiedi S., Rosmawati N., Hou H.K. 2008b. Seismic Stability Analysis of the Largest Malaysian Sanitary Landfill, International Conference on Construction and Building Technology (ICBBT) 2008, Kuala Lumpur, June 16-20, 2008.

Sharma, H.D. and Goyal, H. K. 1991. Performance of a hazardous waste and sanitary landfill subjected to Loma Prieta earthquake, Proc. 2nd ICRAGEESD, St. Louis, Vol. 2, pp 1717- 1725.

Singh S. and Murphy B. 1990. Evaluation of the Stability of Sanitary Landfills, *Geotechnics of Waste Fills – Theory and Practice*, ASTM STP 1070, Avrid Landra, G. David Knowles, editors, American Society for Testing and Materials, Philadelphia, 1990.

Singh S. and Sun J.I. 1995. Seismic evaluation of municipal solid waste landfills, proc. Of Geoenvironment 2000, ASCE specialty conference, New Orleans, Louisiana, *ASCE Geotechnical special publication,* 46(2): 1081-1096.

Sivapalan K., Yunus M.N.M., Kamaruzzaman S., Samsuddin A.H. 2004. Energy potential from municipal solid waste in Malaysia, *Renewable Energy*, Elsevier, 29(4): 559-567.

Tonkin and Taylor Group 2005. Bukit Tagar Landfill Project Brochure, Available: http://www.tonkin.co.nz/projects/pdfs/BukitTagarLandfill.pdf [22 May 2010].

United States Environmental Protection Agency 1993. *Solid Waste Disposal Facility Criteria*, Document No. EPA 530-R-93-017, November 1993.

WES (Waterways Experiment Station) 1994. HELP, Hydrologic Evaluation of Landfill Performance, Version 3.07, Environmental Laboratory, US Army Corps of Engineers.

Xuede Q., Koerner R.M., Gray D.H. 2001. *Geotechnical Aspects of Landfill Design and Construction*, 1st ed., Prentice Hall, New Jersey, NJ, USA.

Zekkos (Zeccos) D. P. 2005. Evaluation of Static and Dynamic Properties of Municipal Solid Waste, PhD thesis, Department of Civil and Environmental Engineering, Univ. of California, Berkeley, California, USA.