STABILITY ANALYSIS ACCORDING TO DIFFERENT SHEAR STRENGTH CONCEPTS EXEMPLIFIED BY TWO CASE STUDIES

Jan Bauer, Florian Koelsch and André V. A. Borgatto
Technical University of Braunschweig, Leichtweiss-Institute,
Dept. of Waste and Resource Management,
Beethovenstr. 51a, Braunschweig, Germany

ABSTRACT

Stability analysis for landfills of municipal solid waste can be conducted according to different analytical calculation methods. The conventional calculation method has been transferred from soil mechanics. The method was invented in the 1920s by Bishop. An advanced method was presented in the 1990s in Germany. It is basically an extended Bishop method which has been adjusted to some specific strength properties of MSW. Meanwhile, the advanced method became technical standard in Germany. Both methods lead to different results in stability analysis regarding the factor of safety as well as the failure mechanism. Due to those differences, engineers may find different conclusions for mitigation and safety measures.

Stability analysis is basically a modelling process. Subsequently, only the comparison of calculation results and empiric observations allow a validation of the physical models behind the analysis. Concerning the validation, failures are the most useful events, since they enable back calculation. The following presentation introduces the advanced strength concepts and the stability analysis exemplified at two landfill failures, the back-calculation of the most recent landfill failure which happened in February 2005 on Leuwigajah dumpsite in Bandung, Indonesia. Regarding the number of casualties and the volume of waste, it was the heaviest failure, which ever happened. The second slope failure case to be reviewed occurred in June 1991 on the Bandeirantes landfill located in São Paulo, Brazil. The following article presents the results of the forensic analysis of both cases and the back-calculation of the events. Both alternative calculation methods were used. The results will demonstrate significant differences between the two methods.

Keywords: Landfill Stability, Stability Analysis, Strength Concept, Municipal Solid Waste (MSW)

Proceedings of APLAS Sapporo 2008
The 5th Asian-Pacific Landfill Symposium
Sapporo, Hokkaido, Japan, October 22 – 24, 2008

INTRODUCTION

Stability of landfills is one of the major geotechnical tasks in landfill design and operation. In Germany a technical recommendation reflecting the state of art in stability analysis released by the German Geotechnical Society. Thus the stability analysis for landfills of municipal solid waste can be conducted according to different analytical calculation methods. The conventional calculation method has been transferred from soil mechanics. The method was invented in the 1920s by Bishop. An advanced method was presented in the 1990s in Germany. Basically it is an extended Bishop method which has been adjusted to some specific strength properties of MSW. The bearing capacity of MSW consists of shear resistance of the granular parts (basic matrix) and tensile forces of fibrous components which contributes as reinforcement to the entire material strength. The parameters shear resistance and tensile strength are usually determined in separated big scale laboratory tests. Direct tensile tests allow separating the part of the fibrous cohesion due to the fibrous components. Big scale laboratory tests are essential to determine the mechanical behaviour of municipal solid waste including all its components. Although the German recommendation provides an empirical database of shear strength parameters for MSW rated by the recommended classification system. From this approach the additional tensile strength part is incorporated in the extended calculations.

The advanced method became technical standard in Germany. Both methods lead to different results in stability analysis regarding the factor of safety as well as the failure mechanism. Due to those differences, engineers may find different conclusions for mitigation and safety measures. Stability analysis is basically a modelling process. Subsequently, only the comparison of calculation results and empiric observations allow a validation of the physical models behind the analysis. Concerning the validation, failures are the most useful events, since they enable back calculation.

The essential knowledge about waste mechanics has significantly improved over the last decade. However, there are still open questions particularly about the influence of regional parameters such as tropical climate conditions as well as influences of variations in landfill operation and waste composition. Several heavy landslide events occurred in countries all over the world during the last years (Table 1). Forensic analysis and back-calculations were conducted in some cases (Kavazanjian et. al, 2005; Koelsch et. al, 2005). It is worth to note that almost all landfill collapses are a consequence of an excess of water inside the landfill e.g. after heavy rainfalls. In combination with other boundary conditions water is often the triggering factor of the collapse (Bauer et. al, 2007). It was one special task of the analytic work to check whether the existing calculation models for landfill stability covers those cases and whether they reflect the stability correctly.

Table 1: Landfill catastrophes of the last years (Muennich et. al, 2006)

Year	Location	Cause of failure	Volume displaced
1997	Bogota, Colombia	Pore pressure caused by leachate recirculation	$800 * 10^3$ m^3
1997	Durban, South Africa	Pore pressure caused by co-disposal of liquid waste	$160 * 10^3$ m^3
2000	Manila, Philippines	Shear failure following heavy rainfall	$13–16 * 10^3$ m^3
2005	Bandung, Indonesia	Mechanical failure caused by fire and heavy rainfall	$2,700 * 10^3$ m^3

STABILITY ANALYSIS

Basics

Municipal solid waste (MSW) is a composite material. The strength characteristic is partly similar to other composite materials such as reinforced soil. In those materials shear strength is generated by an interaction of friction and tensile forces. The tensile forces are incorporated by the fibres and foils which the MSW contains. Those components generate a reinforcement effect. The contribution of the reinforcement to shear resistance is called fibrous cohesion. In total, the shear strength consists of cohesion, friction (related to granular components) and fibrous cohesion (related to reinforcement materials).

The kind of interaction of different sources of shear resistance has some specific consequences to the bearing behaviour of MSW. Other than friction forces, reinforcement effects are anisotropic and non-linear. Due to the common waste disposal procedures, reinforcement components (fibres, foils, sheets) are placed mostly in horizontal direction. Incorporation of tensile forces depends on the angle between main fibre direction (horizontal) and displacement. Developing of fibrous cohesion follows the same characteristic. Due to this anisotropy effect, the Mohr-Coulomb failure envelope is not valid. Subsequently, evaluation of triaxial compression test does not deliver a correct Mohr envelope. Some more obstacles arise for geotechnical testing methods when applied to MSW. Since the developing of fibrous cohesion is limited by the tensile strength of the fibres, the total shear strength is not continuously increasing with normal stress, but also restricted. Therefore, it is not permitted to extrapolate shear strength using testing results in lower range of normal stress. The different character of friction and fibrous cohesion in stress-strain behaviour implies distinguished testing procedures and methods.

Corresponding to the method of material testing and kind of material parameters, different calculation methods are in use.

CALCULATION METHODS

Conventional method

Conventional slope stability calculations are being conducted according to the conventional Bishop method of slices (Figure 1) or similar concepts. Strength properties are described by the parameter cohesion c and angle of internal friction φ according to the Mohr-Coulomb failure criteria. There is the significant obstacle, that those parameters do not reflect the bearing behaviour of MSW exactly as pointed out above.

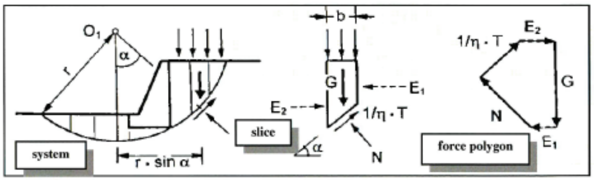

Figure 1: Bishop method of slices

Advanced method: Fibrous cohesion

Slope stability calculations considering the fibrous cohesion (reinforcement effect) are based on the Bishop method, too. However, the advanced method uses an adjusted version of Bishop method. Basically, the shear law has been extended.

Shear law	$T = N * \tan \varphi + c * 1 + \tau(z\alpha)$
Fibrous cohesion	$(z\alpha) = z * a_\zeta * \sin (1,5 \text{ x } \alpha)$
where is	
tensile stress	$z = \sigma_v * \tan \zeta$ (limit $z < zmax$)
normal stress	$\sigma_v = G/b$ (normal to main fibre direction)
transmission factor	$a_\zeta = 0.7 - 1.1$

The advanced method differs from the conventional method by the term of $\tau(z\alpha)$, which has been added to the shear law. The term $\tau(z\alpha)$ models the shear resistance generated by tensile forces z (reinforcement effect). Finally, the shear law is transformed to:

$$T = \frac{G \cdot \tan\varphi + c \cdot b + \left[\mathrm{G} \cdot \tan\zeta \cdot \mathrm{a}_{\xi} \cdot \sin(1.5 \cdot \alpha)\right]}{\frac{1}{\eta} \cdot \sin\alpha \cdot \tan\varphi + \cos\alpha}$$

All added terms are indicated by squared brackets.

The extended shear law is as well incorporated in a conventional slope stability software, commonly used for geotechnical applications.

CASE STUDY 1 - BANDUNG

Bandung is the capital of the Western Java Province in Indonesia. The population of Bandung Metropolitan area accounts to approximately 6 million. Several dumpsites are operated in Bandung Metropolitan area, with the Leuwigajah dumpsite as the largest one. 4500 t municipal solid waste per day are delivered to the site. The site is operated by three different authorities, the City and the District of Bandung, as well as the City of Cimahi. The dumpsite is located within the boundaries of Cimahi. It was established in a narrow valley in the outskirts of Leuwigajah, a neighbourhood of Cimahi. From a hydrogeological point of view, the valley is a suitable site. The subsoil consists of rock covered by a thin layer of 1 m of silt or clay material, performing as a natural barrier. Before the waste disposal started, small water streams were running through the valley in wet season (October till April) carrying the surface run-off. Precipitation is high in the region, between 1500 and 2000 mm per year while rain distribution is significantly non-uniform. Heavy rainfall and thunderstorms are common during wet season. Waste disposal procedure is on a basic level. Dumping activities started from the top of the valley just dropping the waste over the edge. Compaction machines were in place, but appeared recently in a poor condition. It is not clear, whether they have been in use or not. West Java EPA noticed the dumping area to 6.5 ha, but the site was looking much bigger. The natural landscape of the valley showed a small slope of approximately 5-10 % in the bottom of the valley and a slightly higher slope in the upper end. Before the failure happened, the maximum height of the dumpsite arose to 60-70 m. According to local experts, the front slope facing the Open valley showed a slope angle between 30° and 45°.

The landslide happened on February 21st, 2005 at 2.00 A.M. After 3 days of heavy rain, 2.7 million cubic meters of waste started sliding down the valley. The waste covered a 200-250 m wide stripe on a length of 900 m. It is not finally clear how quick the landslide occurred. It seems to be very likely that it took not more than a few minutes. Witnesses reported a roll of thunder somehow like an explosion. Regarding the speed, those observations indicate that the waste came down quite similar to an avalanche. The death toll was high. Down the valley one small settlement was destroyed by half (see Figure 2, close to upper left corner), while another village faced light damages. Rescue teams uncovered 147 dead bodies out of the waste. Rescue activities have been carried out only in the area close to the two settlements. It is not clear, whether there were people staying overnight on top of the dumpsite, which probably were killed in other areas. Rescue works last for about 3 weeks. They were massively hindered by landfill fires. No more survivors could be found.

Figure 2 shows a satellite image generated by the Department of Geodetic of the Bandung Institute of Technology (ITB). The winding line in the right side of the image, which splits the dark and the light area, indicates the edge of the remaining slope. The former borderline of the dumpsite is illustrated by the yellow line in figure 2. Following the waste far to the left, surrounding untouched rice fields can be seen. The image indicates that the area now covered by waste has 4-5 times the size of the area where the waste originally was placed.

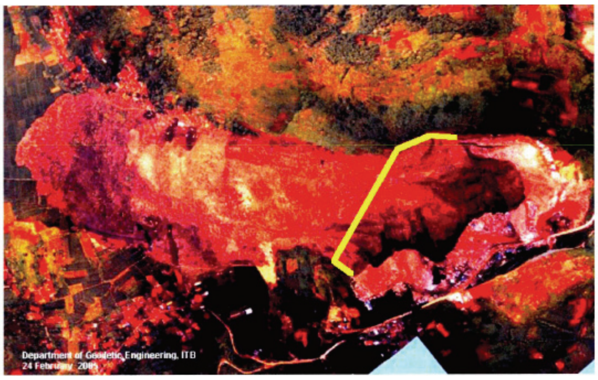

Figure 2: Satellite image of Leuwigajah dumpsite (taken by ITB)

Material parameters

The material parameters used in the calculation have been collected from forensic geotechnical testing and from literature. The strength parameter (φ, c and ζ) for the MSW were varied in the range indicated in Table 2.

Table 2: Stability analysis Leuwigajah - material parameters

Parameter	Source	Conventional	Advanced
Subsoil (rock)	Geotechnical testing		
φ [°]		45	
c [kPa]		20	
γ [kN/m³]		20	
Clay layer	Geotechnical testing		
φ [°]		12	
c [kPa]		10	
γ [kN/m³]		18	
MSW			
φ [°]	Variation	20-45	20-45
ζ [°]	Variation	n.a.	15-35
c [kPa]	Variation/Literature	10-50	10
γ [kN/m³]	Literature	11	11

Calculation results

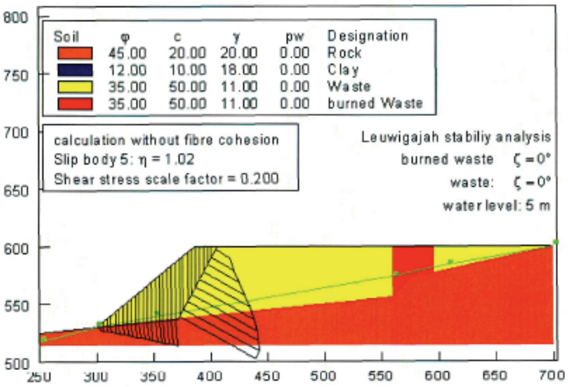

Figure 3: Conventional calculations - unfavourable sliding figure close to the slope

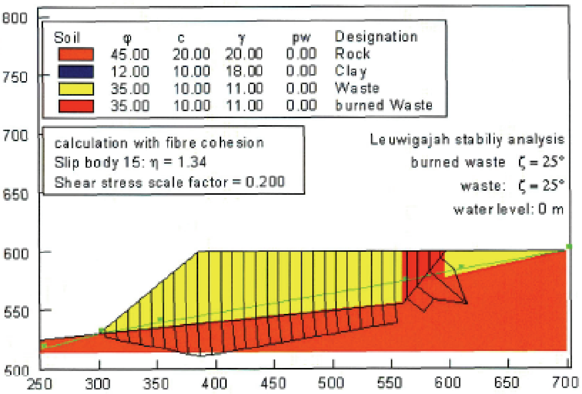

Figure 4: Advanced method - unfavourable sliding figure in the landfill Centre

There are two major differences between the two calculation methods. On one hand the shape and the location of the most unfavourable slip body is different. A typical sliding figure obtained from conventional calculation is shown in figure 3. The sliding figure follows the clay layer in the deep joint and crosses the waste with an angle of 45°+φ/2 in the upper part. The advanced method delivers different and switching results. The most unfavourable sliding figures are located either close to the slope (as shown in Figure 3) or close to the centre of the landfill (Figure 4). The result strictly depends on the proportion of friction (φ) and fibrous cohesion (c). The sliding figure tends to the centre with increasing fibrous cohesion. One could say that the sliding figure moves away from the high resistant areas and tries to minimize the Cross section distance through MSW. It literally seeks the weak parts of the construction, i.e. the clay layer.

On the other hand, global safety is higher according to the advanced calculations. This is owed to the fact, that a tensile angle ζ= 35° (for example) may deliver as much as 210 kPa of (fibrous) cohesion, provided the normal stress is sufficient and the bottom angle of the slice has a favourable direction. Figure 5 illustrates the results of stability analysis according to both different methods while varying the reinforcement properties (c respectively ζ). After hundreds of variations, results were condensed to this chart, which contains the results for high strength (conventional: c = 50 kPa, advanced: ζ = 35°). The figure shows different curves for different water levels above the clay layer. Water level was increased from 0 to 15 m. Factor of safety drops with rising water level. According to the conventional method the slope can stand a water level of 0 m (if friction angle $\varphi < 30°$), 5 m ($\varphi < 35°$) or 10 m ($\varphi < 40°$). However, the sliding figure is always close the slope. It is very likely, that in Leuwigajah case the sliding figure was close to the centre. The results of advanced calculations are indicated by dashed lines in Figure 5. In case of large slip bodies the markers have a red margin. The figure demonstrates that the factor of safety does not increase anymore after the slip body switched to the centre. That means that the friction angle has not much impact on the global safety of the large slip bodies.

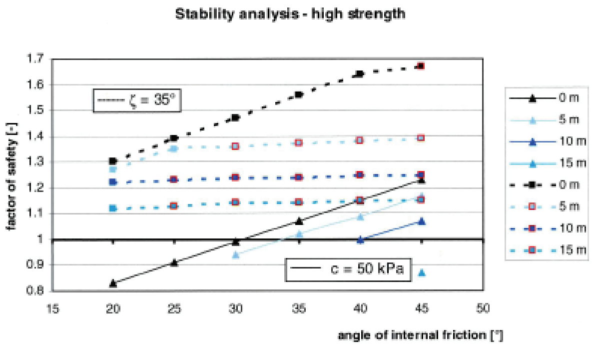

Figure 5: Calculation results - high strength, varying friction and water level

In fact, the MSW strength properties do not have much impact on safety at all, because the sliding surface of the large slip bodies is mostly leading across the clay layer. However, it requires a certain amount of shear resistance to switch from the small to the large sliding bodies. The Figure 5 proves another fact. Even with 15 m water level on top of the clay layer, threshold has not been exceeded, yet. There are two different scenarios for the Leuwigajah landfill failure:

Water: With common strength properties the landfill fails when the water reaches a level of 22-23 m above the clay layer

Fire: Since the sliding figure mostly passes through the clay layer, the part, where the figure crosses the MSW is small. However, local weaknesses may be important and may trigger the failure. Local disturbance may be due to landfill fire or construction measures. In Leuwigajah some indicators have been found, that the MSW shear resistance was weakened due to fire. Figure 6 presents the corresponding stability analysis for this case.

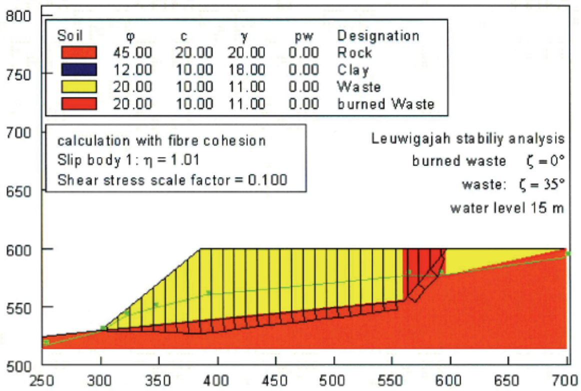

Figure 6: Advanced method - burned area in the landfill center

CASE STUDY 2 - BANDEIRANTES

The Bandeirantes sanitary landfill is located in Sao Paulo and is one of the largest sanitary landfills in the country of Brazil. The landfill receives approximately 6,500 tons of waste daily which is nearly half of the amount that is produced in the city of Sao Paulo. With a population of 16 million people it is one of the largest cities in the world. The landfill was built 30 years ago. The landfill covers an area of 1.50 km^2 and has a storage capacity of about 30 million tons of waste. In June 1991 the slope of the sector AS-1 with a height of more than 100 m collapsed after several days of rainfall and 65,000 m^3 of waste slid down and covered an area of about 45,000 m^2 (Figure 7).

A back-analysis of the cross section D of the Bandeirantes landfill was made according to the advanced calculation method (Borgatto, 2007). Subsequently a comparison was made between these results and the results of the IPT report (1991) which represents the official causal analysis and back-calculation of the slope failure.

Figure 7: Slope failure of Bandeirantes landfill, Sao Paulo, Brazil in 1991 (Borgatto, 2007)

Material parameters

In order to make a comparison of the results possible, in the first step the resulting parameters of the IPT report were used as well as the failure model according to Mohr-Coulomb. The unit weight of MSW used for drained conditions and no drained were 10 kN/m^3 and 13.5 kN/m^3 respectively. The shear strength parameter values of cohesion $c = 13.5\ kN/m^2$ and angle of internal friction $\varphi = 22^\circ$ were used respectively. According to the hydraulic conditions and the assumed high water table inside the landfill body the cohesion value resulting from the back-calculation seems not to correspond to the in-situ conditions.

The landfill drainage system conditions were represented through the variation of the parameter r_u, In analyses that consider limit equilibrium method, that parameter works as an application of a pore-pressure value on the bottom of each slice corresponding r_u times the total vertical stress.

Furthermore, for the inclusion of the reinforcement effect of the fibres, the parameter angle of internal tensile force (ζ) was added in the formulation as a value of 35° (fresh waste). This value was adopted based on the morphologic classification of a Brazilian MSW sample according to BORGATTO (2006). Values of dimension 1 and 2 were found in that work above 30 weight-% and then applied to the German technical recommendation GDA E 2-35 (DGGT, 1997). The age of the waste in the failure section (Figure 8) was considered fresh (1 year-old).

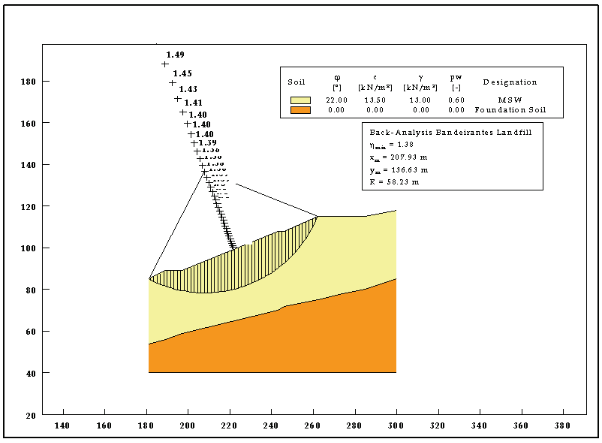

Figure 8 – Cross section D of the Bandeirantes landfill (Borgatto, 2007)

Calculation results

The back-analysis of the Bandeirantes landfill failure considering the reinforcement effect of the fibres was compared to the analysis presented in the Report nº. 29.596 IPT (1991) which was analysed with the classic methods of the soil mechanics. Comparison among the results is presented in Table 3.

Table 3 - Comparison among the results IPT and back-analysis considering the reinforcement effect of the fibres (Borgatto, 2007).

	IPT Report (classic methods of soil mechanics)			**Back-analysis** (with inclusion of fibre reinforcement effect)		
Parameters	r_u = 0.0	r_u = 0.3	r_u = 0.6	r_u = 0.0	r_u = 0.3	r_u = 0.6
Angle of friction ↑'(°)	22.00	22.00	22.00	22.00	22.00	22.00
Cohesion c'(kN/m^2)	13.50	13.50	13.50	13.50	13.50	13.50
Unit Weight (kN/m^3)	13.00	13.00	13.00	13.00	13.00	13.00
Angle of internal tensile force ζ (°)	-	-	-	35.00	35.00	35.00
Safety Factor (SF)	2.06	1.55	**1.00**	2.25	1.83	**1.38**

The safety factor resulting from the back-analysis (SF = 1,38) for the pore-water (r_u = 0,6) indicate that the slope was stable in the worst condition. Applying in the same analysis a unitary safety factor (SF = 1) the value of the cohesion found is presented (Table 4).

Table 4 - Comparison among the results IPT and back-analysis considering the reinforcement effect of the fibres in the failure condition (Borgatto, 2007).

Parameters	**IPT Report** (classic methods of soil mechanics)	**Back-analysis** (with inclusion of fibre reinforcement effect)
	r_u = 0.6	r_u = 0.6
Angle of friction ('(°)	22.00	22.00
Cohesion c'(kN/m^2)	**13.50**	**2.00**
Unit Weight (kN/m^3)	13.00	13.00
Angle of internal tensile force ζ (°)	-	35.00
Safety Factor (SF)	1.00	1.01

According to the application of the reinforcement effect of the fibres in a back-analysis of the Bandeirantes sanitary landfill failure, maintaining the same values for angle of friction, unit weight as well as geometry and pore-water-pressure condition (r_u = 0.6) presented in the IPT Report nº. 29965 (1991), however, adding the parameters of reinforcement of the fibres for fresh MSW (angle of internal tensile stress ζ = 35º) and the fibrous cohesion for a unitary safety factor, a cohesion value of 2 kN/m^2 results from the back-calculation that is significantly smaller than the value presented as a conclusion in the IPT Report. As a result from the advanced back-analysis the characteristic cohesion strength is based on the reinforcement effect of the fibrous components as well evidenced due to the age of the fresh waste.

CONCLUSIONS

The forensic analysis of slope failures and landfill slides enable besides the causal research the back calculation of the material properties. Compared to in-situ and laboratory tests the back calculation method supposed to a favourable method but the results depend on the assumption of a characteristic strength concept. Different strength concepts and calculation methods exist for evaluating landfill stability and waste properties. Besides the most common concept based on the soil mechanics consideration with a linear failure envelope according to Mohr-Coulomb an advanced calculation method was presented that takes the waste characteristic reinforcement effect (fibrous cohesion) due to the fibrous components into consideration. The advanced calculation method is an established approach evaluating landfill stability and as well incorporated in the German recommendation (DGGT, 1997).

The stability analysis according to these two different calculation methods was exemplified by two case studies.

The forensic analysis proved why the failure of Leuwigajah dumpsite happened. Using the advanced calculation method, it could be shown, under which circumstances large sliding figures are being generated (instead of those smaller ones located next to the slopes). Modelling the failure mechanism correctly in an analytical calculation is essential for understanding landfill stability. Conventional calculation methods for landfill stability can obtain these results just by accident. In both discussed cases as in others the results are not matching the real observations. In general, waste strength is considerably underestimated in conventional analysis, because the reinforcement effect is not considered correctly. Regarding the overall stability, the underestimation of waste strength may not be a problem; it just makes believe a lower safety. However, it becomes very critical in case stability analysis is conducted aiming to identify critical factors and areas, because it may deliver totally wrong sliding figures. On the other hand strength properties can be attributed to the wrong waste strength characteristic and lead therefore to uncertainties when e.g. hydraulic conditions inside the landfill change and reduce the strength.

The stability analysis proved that the failures most likely have been triggered by water pressure in the soft subsoil and the deep landfill zones probably in combination with a severe damage of reinforcement particles due to a smouldering landfill fire (in Leuwigajah case). This result addresses a specific stability problem in tropical countries. Since precipitation is high, but non-uniform, both events may happen. On one hand there are acute drainage problems coming along with pore-water pressure in soft soils or high water tables inside landfills. On the other hand, an extreme risk of landfill fires exists during the dry period. It is an important task to adjust landfill operation in those countries.

Regarding landfill construction it is necessary to ensure proper drainage. As the Leuwigajah case has shown, the strength of the waste is not the major problem, since strength capacity is more than sufficient. It is more important to take care for the weak sections of the landfill construction. Especially the soft soils need protection, no matter whether it is a natural deposit or a technical barrier.

REFERENCES

Bauer, J., K. Münnich, K. Fricke (2007): Influence of hydraulic properties on the stability of landfills, In: Sardinia 2007, 11th International Waste Management and Landfill Symposium Cagliari, Italy

Borgatto A.V.A, C. F. Mahler (2006): Inclusion of the fibres reinforcement effect in the analysis of slope stability in MSW landfill – Application to Bandeirantes landfill case, Proceedings of The Second Baltic Symposium on Environmental Chemistry (Kalmar ECO-TECH), Kalmar, Sweden

Borgatto A.V.A (2006): Estudo do Efeito Fibra e da Morfologia na Estabilidade de Aterros de Resíduos Sólidos Urbanos. Dissertacao de Mestrado, COPPE-UFRJ. (Study of Fibre Effect and the Morphology in the Stability of Municipal Solid Waste) (in Portuguese)

DGGT (1997): Geotechnik der Deponien und Altlasten, GDA-Empfehlungen, 3. Auflage, Deutsche Gesellschaft für Geotechnik e.V. (DGGT) (Hrsg.), Ernst & Sohn, Berlin

Kavazanjian E., S.M. Merry (2005): The 10 July Payatas Landfill Failure, In: Sardinia 2005, Tenth International Waste Management and Landfill Symposium, Cagliari, Italy

Koelsch, F., K. Fricke, C. F. Mahler, E. Damanhuri (2005): Stability of landfills – The Bandung disaster, In: Sardinia 2005, Tenth International Waste Management and Landfill Symposium, Cagliari, Italy

Koelsch, F. (2007): Stability analysis according to different strength concepts, 2nd International Workshop "Hydro-Physico-Mechanics of Landfills", Southampton, UK

Münnich, K., J. Bauer (2006): Monitoring of emssioins and mechanical behaviour of MSW landfills – new techniques for a better understanding of the long-term behaviour", Proceedings of the International Symposium on Technology and Treatment of Solid Waste (Simpósio International de Tecnologias e Tratamento de Residuos Sólidos - SITTRS), Rio de Janeiro

RELATÓRIO IPT, 29956 (1991). Levantamento e Análise das Causas do Escorregamento de Massa de Lixo no Aterro Bandeirantes – AS1, Perus, São Paulo. (in Portuguese)