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Chapter 4.6

Static Stability of Landfills

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1 Introduction

Ensuring landfill stability is the major geotechnical approach during the operation and aftercare of landfills. The stability depends on various parameters such as waste composition, waste compaction, climate conditions, landfill geometry, ground stability and pore water pressure. The following technical recommendations provide an overview on the knowledge about waste mechanics and stability analysis. It particularly addresses the handling of geotechnical tasks related to municipal solid waste. Regarding the mechanical behaviour, municipal solid waste is significantly different from soil. Geotechnical problems of other waste deposits which consist of materials similar to soil may be handled with conventional method of soil mechanics. Same applies to geotechnical tasks of mineral liner systems.

It is well known, that waste deposits may show both extraordinary stability and weakness no matter what kind of landfill geometry, country and waste it is. Photos 1 and 2 demonstrate two cases of landfill failure; on Photo 3 an extremely steep slope is shown.

Photo 1:
Landfill failure -
Maine (USA), 1989

Photo: Richard Reynolds

Photo: Florian Kölsch, Braunschweig, Germany

Photo 2:
Landfill failure - Payatas (Philippines), 2000

Photo: Florian Kölsch, Braunschweig, Germany

Photo 3:
Steep slope - Goettingen (Germany), 1996

2 Waste Mechanics

2.1 Basics

Municipal solid waste (MSW) is a composite material. The strength characteristic is partly similar to other composite materials such as Reinforced Earth. 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 the MSW contains. Those components generate a reinforcement effect. The contribution of the reinforcement to shear resistance is called fibre-cohesion. In total, the shear strength consists of cohesion, friction (related to granular components) and fibre-cohesion (related to reinforcement materials).

This 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 most popular 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 fibre-cohesion follows the same characteristic.

Due to this anisotropy effect, the Mohr-Coulomb failure criterion is not valid. Subsequently, evaluation of triaxial compression tests does not deliver a correct Mohr envelope. Some more obstacles arise for geotechnical testing methods when applied to MSW. Since the developing of fibre-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 fibre-cohesion in stress-strain behaviour implies distinguished testing procedures and methods.

2.2 Shear Strength

2.2.1 Fibre-cohesion

The stress-strain behaviour of the reinforcement components under tension load determines the fibre-cohesion. A new developed tension test under normal load models the loading condition for the reinforcement materials of MSW. Figure 1 shows the relation between tensile stress and normal stress in tension tests under normal load and illustrates the definitions for stress-strain behaviour in this specific test. The non-linear or respectively bi-linear strength behaviour is characterised by two stress ranges. For smaller normal stress, the tensile stress in the MSW sample depends on normal stress. After exceeding the fibrous specific tensile strength, tensile stress remains constant, even in case of increasing normal stress. This stress-strain characteristics is similar to Reinforced Earth theory, where the two ranges are called “anchorage failure” (lower normal stress) and “reinforcement failure” (higher normal stress).

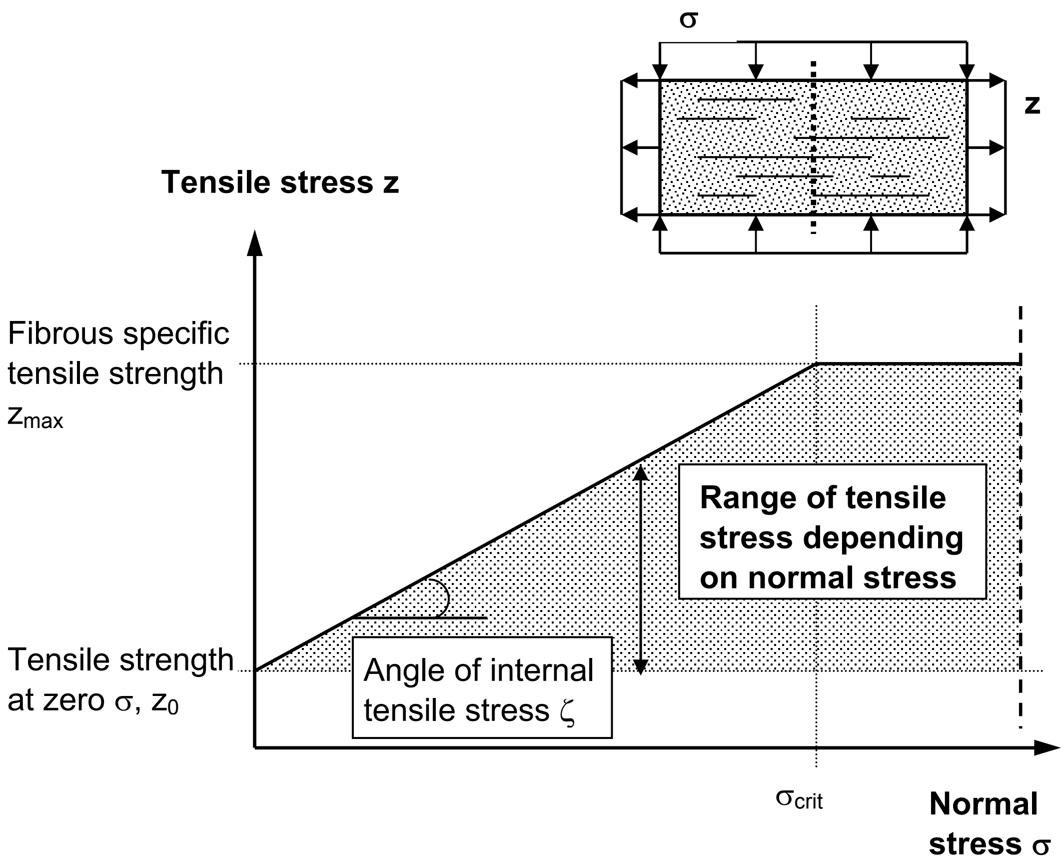

Figure 1: Failure characteristics of fibrous waste material in tension test under normal load

The linear relation between normal stress and tensile stress for smaller loadings is described by a material parameter called angle of internal tensile stress ζ. This angle is determined by conducting several tension tests under different loadings (KÖLSCH, 1995).

The testing principle and procedure is shown in Figure 2, the equipment in Photos 4 and 5.

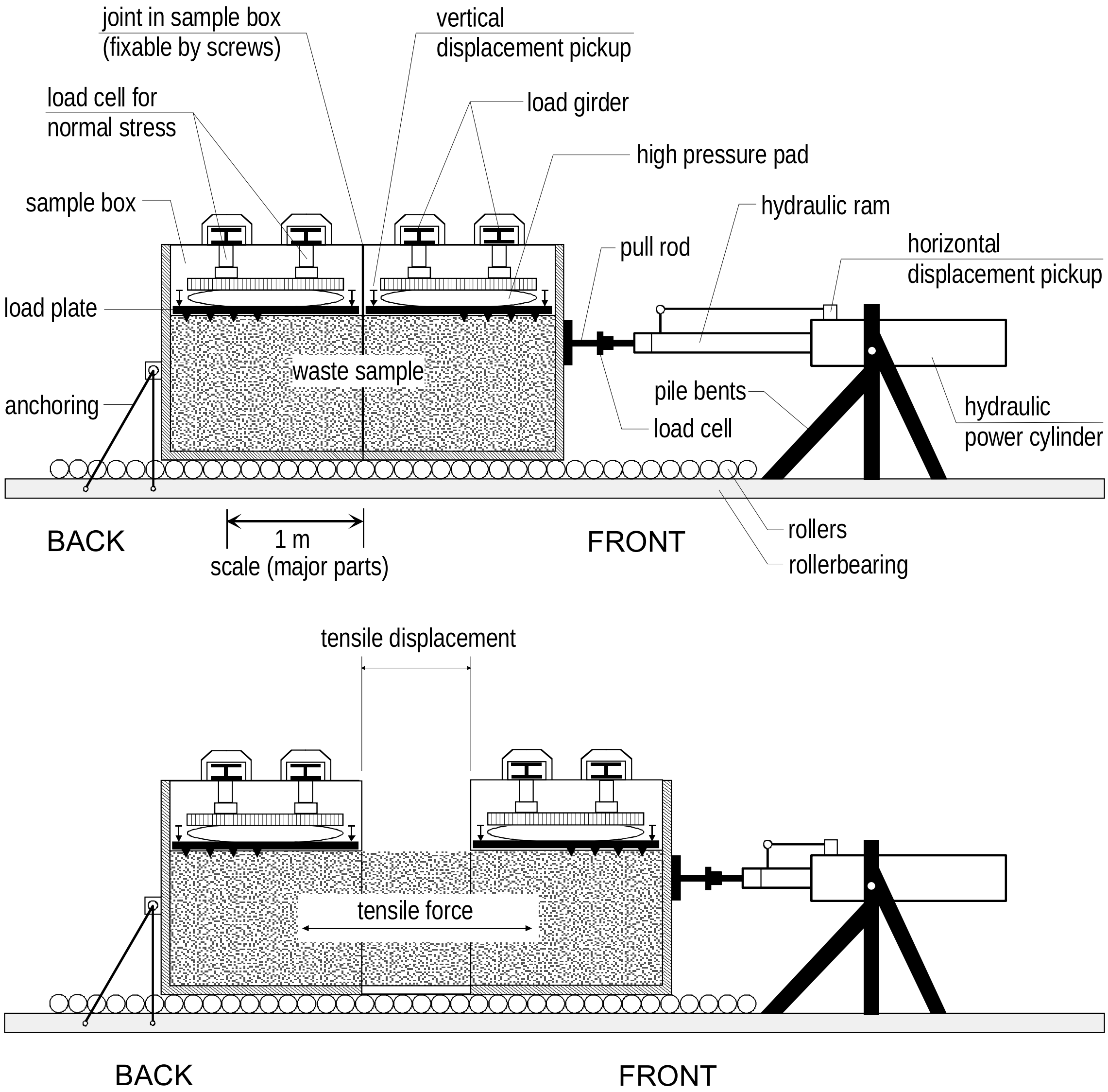

Figure 2: Tension test under normal load – principle and procedure

Photo 4:
Tension test under normal load – equipment

Photo: Florian Kölsch, Braunschweig, Germany

Photo 5:
Tension test under normal load – equipment

Photo: Florian Kölsch, Braunschweig, Germany

2.2.2 Friction

The friction properties are investigated in direct shear test. To facilitate unmodified municipal solid waste, a large shear box is required. Photo 6 shows a shear box with a shear plane area of 1 x 1.80 m. The large shear box contains a waste sample of approximately 2.5 m^3. The box is movable, since the placement of the waste sample needs to be done at a landfill site.

Photo 6:
Large shear test – equipment

Photo: Florian Kölsch, Braunschweig, Germany

Nevertheless, smaller shear boxes may be used for shear testing, too. Waste samples need special treatment to allow shear testing in smaller shear frames. Segregating larger waste particles is a common method. Regarding the maximum size of particles, standards of soil mechanics do not apply. Good results have been experienced by limiting maximum particle size to 0.2 x frame size (area) and 0.5 x frame height.

The testing procedure of large shear tests is similar to the conventional direct shear test. The specimen is placed into the shear box and normal load is applied on the sample. When the consolidation of the sample has finished, one frame is moved against the other (see Figure 3). Shear deformation is increased till the shear strength is exceeded. After the failure, either normal load is increased or a new sample is placed applying a higher normal load. Three stages of normal load are usually conducted, while the highest normal load should correspond to the stress situation on site.

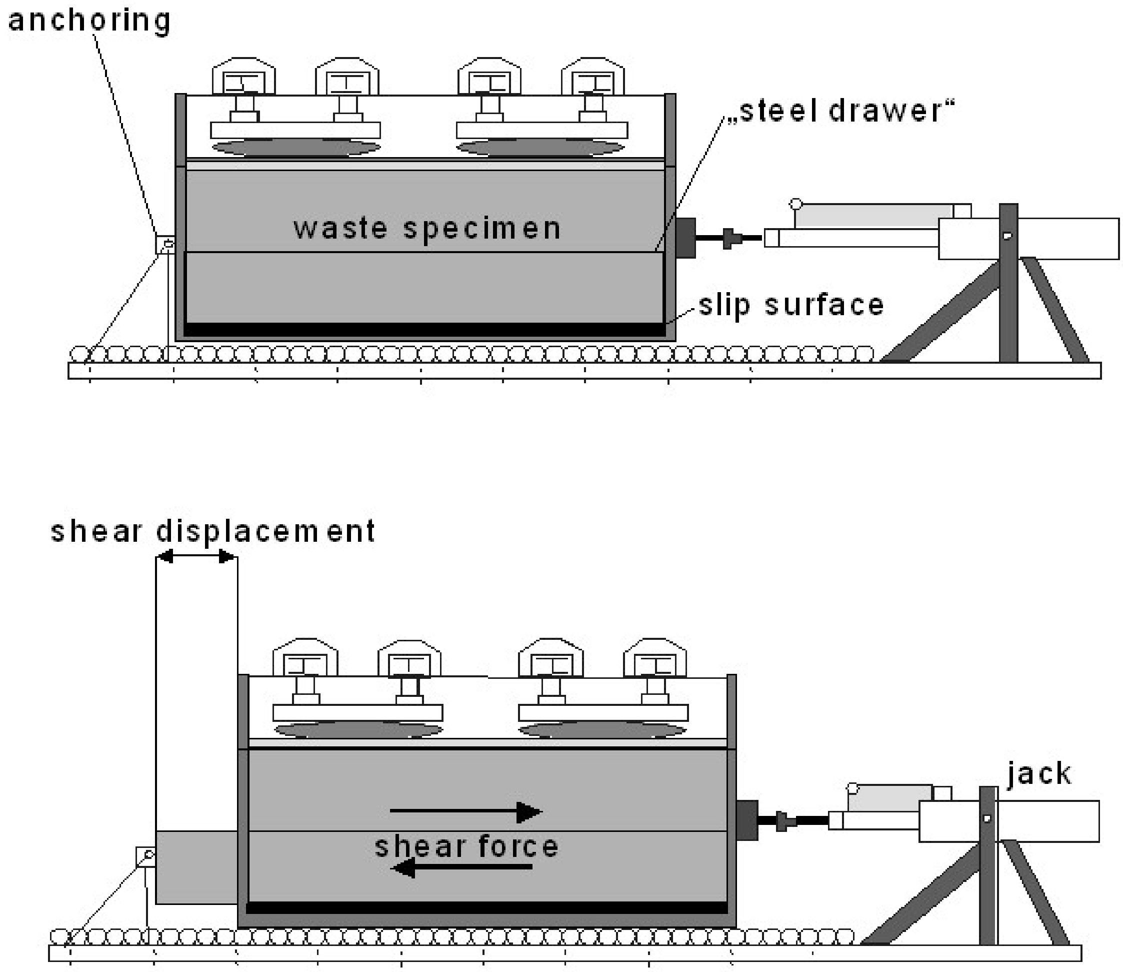

Figure 3: Large shear test – testing procedure

From direct shear tests two material parameters can be obtained, the internal angle of friction φ and the cohesion c. Figure 4 illustrates the result of a direct shear test on MSW (COLLINS et al., 1997).

Results of direct shear tests need to be evaluated thoroughly. Shear tests in smaller frames, which require the segregation of larger waste particles, do not reflect the real shear strength of waste, but just the friction properties. On the other hand, shear tests on unmodified MSW regularly show higher shear strength than one could expect from friction properties. This is due to the fact that in direct shear tests fibre-cohesion may be activated, although the shear plane is approximately parallel to the main fibre direction. In stability calculations it needs to be considered, that material values obtained from tension and shear tests may overlap. Non-linear shear planes (curves) as shown in Figure 4 may result from those overlappings.

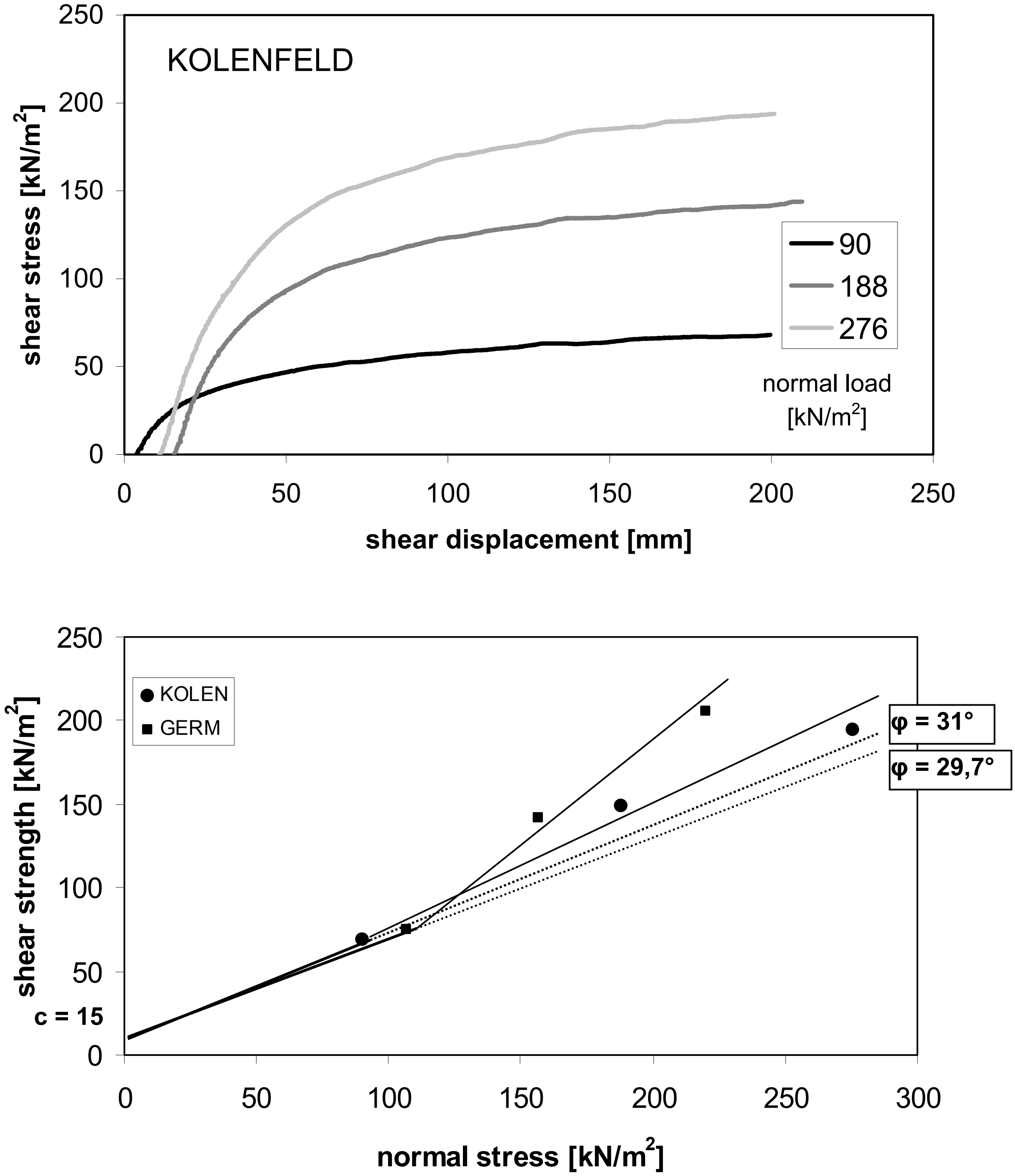

Figure 4: Direct shear test on MSW – results: stress-strain (left), non linear shear planes (right)

2.2.3 Deformation Dependent Shear Strength

As described above, there is no way to determine the shear strength of MSW unless the material is isotropic. Usually, MSW sample do not show failures under triaxial load due to the effect that the reinforcement (fibres) becomes stiffer as the normal load increases. However, triaxial compression test may provide data on stress-strain-behaviour of MSW, even shear strength parameter (φ, c) may be determined, but for certain deformations, only. This concept has been named “deformation dependent shear strength”.

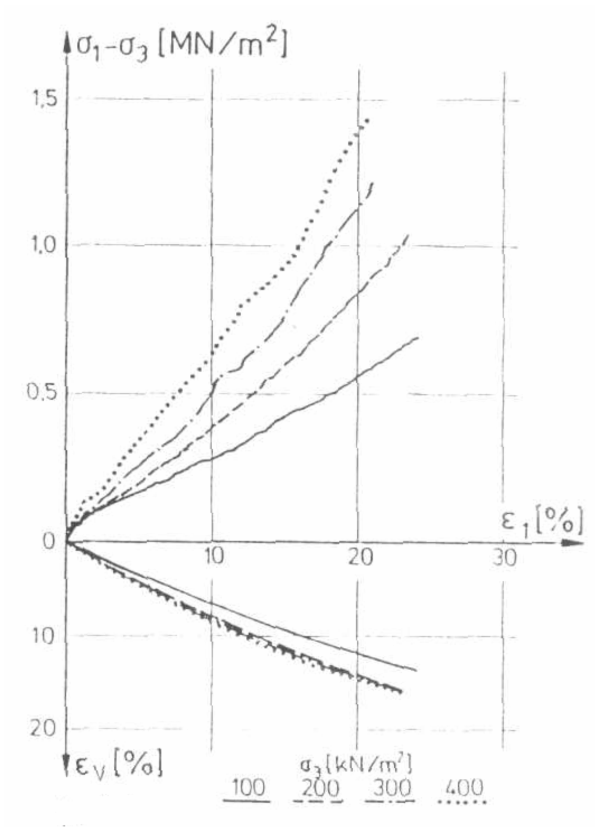

Figure 5: Results of triaxial compression test (JESSBERGER et al. 1995)

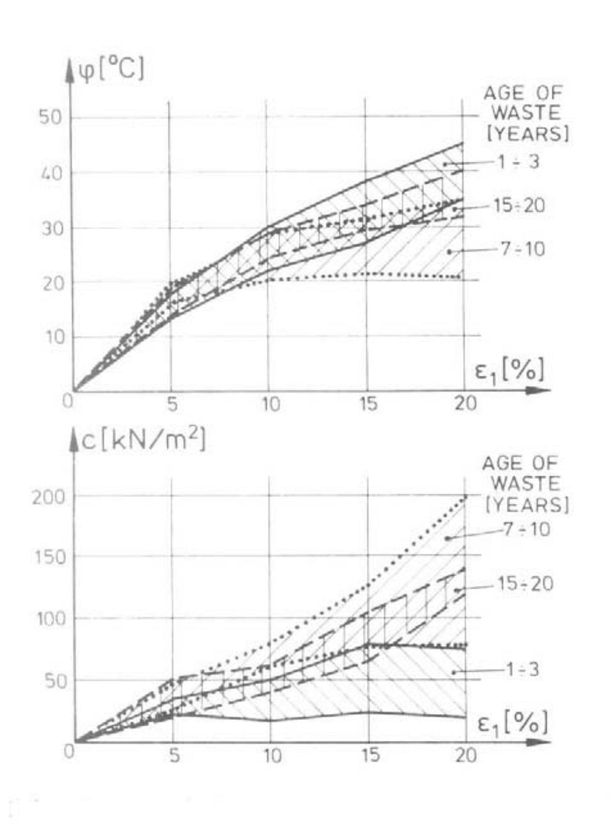

Figure 6: Deformation dependent shear parameters (JESSBERGER et al. 1995)

Figure 5 shows the result of a triaxial compression test on MSW. The sample has a diameter of 100 mm; vertical deformation is limited to 25 %. The stress-strain curve demonstrates that the sample does not fail. Figure 6 illustrates the evaluation concept of deformation dependent shear parameters. For different deformations the friction angle φ and the cohesion c is determined assuming a Mohr-Coulomb yielding condition. The deformation dependent evaluation results in a function with $\varphi = f(\varepsilon_1)$ and $c = f(\varepsilon_1)$. The shear parameters develop with increasing vertical deformation depending on the waste properties.

3 Stability Analysis

3.1 Material Parameters

3.1.1 Waste Sampling

Procedures of waste sampling can be generally distinguished into two groups:

- fresh MSW (prior to landfilling)
- degraded MSW (after landfilling)

Samples of fresh MSW can be collected during waste collection and delivery at the landfill. Samples of waste, which has already been dumped at the landfill, are more difficult to get. In fills with a depth up to 7 m, waste samples may be dug out by means of excavating (Photo 7).

Excavations are suitable and affordable measures, but significance is limited due to the small depth accessible by excavations. For higher landfills, drilling is the only opportunity to get waste samples. Drilling diameter may be as large as 1000 mm (Photo 8). Useful diameter starts at 100 mm. Those small bore holes may be later used as 2’’-montoring wells (Photo 9).

Similar basic handling rules apply for all different methods of waste sampling. The waste samples must be distinguished according to the source of waste (location, layer in landfill). In terms of large drilling, the waste will be placed corresponding to the depth of drilling (Photos 10 and 11).

Photo 7: Excavation

Photo: Florian Kölsch, Braunschweig, Germany

Photo 8:
Drilling (800 mm)

Photo: Florian Kölsch, Braunschweig, Germany

Photo 9:
Drilling (100 mm)

Photo: Florian Kölsch, Braunschweig, Germany

Photo: Florian Kölsch, Braunschweig, Germany

Photo 10:
Large drilling – exploited waste samples (one heap / 2 m depth)

Photo: Florian Kölsch, Braunschweig, Germany

Photo 11:
Large drilling – exploited waste samples (one heap / 2 m depth)

3.1.2 Waste Analysis

The analysis of municipal solid waste for geotechnical purpose requires a specific procedure which is different from conventional geotechnical methods. Those methods may be useful for waste materials with geotechnical properties similar to soil. The following paragraph provides an overview on the waste analysis procedure.
The first step of analysis comprises of the identification and classification of the waste. For this purpose, relevant information needs to be recorded such as:

- kind of delivery (waste truck, bulky waste truck, container truck, open truck)
- kind of mechanical/biological pre-treatment
- source (households, commercial, industry, waste water plant, construction site)
- structure (MSW mixture, sludge, fibrous mix, granular mix)
- dominant portions (soil, debris, MSW, sludge, bio-waste)

If not yet done, fresh waste on delivery needs to be recorded in order to check for data on mass [t], volume [m^3], homogeneity and consistency.

The main part of the identification is the assorting analysis regarding the kind of materials. Since the assorting procedure needs to remain manageable, groups of materials are defined corresponding with their geotechnical effect and behaviour. The groups are:

- paper/cardboard
- synthetics – soft (rubber, foils, tetra, leather, textiles)
- synthetics – rigid (plastics)
- metals
- minerals (glass, ceramics, ashes, soil)
- wood
- organics (vegetables, food, fruits, green)
- small particles I: 8-40 mm
- small particles II: < 8 mm

For geotechnical purposes, size, shape and condition of all material groups need to be determined. The size of particles will be screened at 40, 120, 500 and 1000 mm. After splitting the material groups into different sizes, the shape of all groups will be examined. Four types of shape will be distinguished:

- Dim 1 (one side long, two short): wires, cables, ropes
- Dim 2 (two sides long, one short): foils, sheets
- Dim 3 (all sides long): cubes, boxes, rocks
- Dim 0 (all sides short i.e. < 40 mm)

Water content and biological stability are the major parameter to identify the waste condition. In most cases, particularly when the waste analysis focus on old waste, it is sufficient to determine both parameters using the smaller waste particles (0 - 8, 8 - 40 mm). For both parameters laboratory standards are available. Water content is a basic parameter in soil mechanics as well as in other fields. Biological stability may be measured as respiration (aerobe) or as gas generation (anaerobe). Standard testing duration in Germany is 4 days (respiration) respectively 21 days (gas generation).

3.1.3 Material Parameters

Material parameters for waste strength are available for various different waste materials. Average numbers have been condensed by evaluating the results of strength test on waste samples linked with the waste analysis of those samples.

Table 1: Geotechnical parameters for MSW and MBT-material

Parameter	Unit	untreated MSW	MBT-waste	comments
Respiration activity AT_4	mg O_2/g TS	> 5	< 5	
dry density ρ_d	t/m^3	0.2-0.5	0.2-0.7	loose dropped
		0.5-1.0	0.8-1.5	compacted
Shear strength (anisotropic)				
Tensile angle ζ	°	25-35 dim 1+2 > 30%	10-14 dim 1+2 < 20%	
friction angle φ_{GM}	°	25-30	30-35	
Cohesion c_{GM}	kPa	<10		
Shear strength (deformation dependent)				
Friction angle $\varphi_{\varepsilon 1}$	°	ε_1 = 0 %: 0 ε_1 = 10 %: 20-25 ε_1 = 20 %: 22-35		
Cohesion $c_{\varepsilon 1}$	kPa	ε_1 = 0 %: 0 ε_1 = 20 %: 22-35		
modulus of stiffness E_S	kN/m^2	$E_S = -a + b*\sigma$ a: -100 bis -300, b: 10-13		

MSW: Municipal solid waste MBT: Mechanical biological treatment

However, most results have been obtained from samples in Western countries. Those numbers may be utilized under other circumstances like tropical climate conditions as well, but need to be handled with care. Table 1 provides an overview on material parameters for municipal solid waste referring on the different concepts of material testing. The table basically classifies waste into untreated (raw) waste material and biologically stabilized material (after decay or MBT).

3.2 Calculation

The correct calculation of landfill stability is an ambitious task. The more efforts are spent on calculation, the more realistic the analysis results are. However, small and low landfills in dry areas face significant less risk of landfill failure than high landfills in tropical countries. On the other hand, potential damages and casualties, which a landfill failure may cause, should be considered when choosing an analysis method. Landfills located in sensitive areas like next to housing areas may require more detailed analysis. Considering the crucial lack of financial means in less developed countries it is acceptable to link the efforts to the risk of failure and the amount of potential damage.

According to the results of a risk analysis, one of the methods described below may be chosen. The set of calculation methods is presented in order of efforts beginning with the simplest way. In general, engineers should anticipate calculating the best way using the most advanced geotechnical models, if possible.

In stability analysis engineers should pay attention to the fact that large deformations may develop in MSW, which can lead to incompatibilities with the deformations in the subsoil. This may particularly happen in case the sliding circle crosses both the waste and the subsoil. In this case the mobilized shear strength of MSW depends on the smaller limiting strain of the subsoil.

One major element with a big impact on the calculation results is the safety factor. Safety factors reflect uncertainties of the modelling and calculation methods as well as the anticipated level of safety regarding the possible consequences of failure. Generally, in all areas of mechanics safety factors have been object to permanent discussion. In soil mechanics, the concept of partial safety factors was introduced recently and quickly became state of the art. Based on common experiences, the safety concepts of soil mechanics (overall safety, partial safety) may be used in waste mechanics in a similar way. Larger uncertainties in material parameter (due to testing and sampling problems) may be balanced by higher reserve forces, which are not considered in modelling and calculation (3-dimensional forces, large deformations). However, engineers are always free to calculate with higher partial safety factors, if they judge this to be appropriate.

“Simplified method”

The “simplified method” is basically not an engineering tool, but an empiric method based on experience. It is strictly recommended to use the simplified method under very special conditions, only. It should generally not be considered a common and reliable procedure. There may be situations, where any effort for geotechnical analysis is not worthwhile. In case, thorough geotechnical assessments can not be conducted for some reason, there is a bottom-line, which allows establishing a landfill while waiving any detailed geotechnical consideration. However, the recent landfill failures have proved that geotechnical aspects are very important and should not be simply set aside. The bottom-line, which refers to experience, is defined by:

- landfill height < 15 m
- slope less than < 15°
- horizontal subsurface
- stable subsurface
- leachate collection or reduction measures (no leachate build-up)
- distance to housing area > 300 m

Common geotechnical methods

Slope stability calculations are often conducted according to Bishop's method of slices (Figure 7) describing the material by the parameter φ and c. There is a significant obstacle that those parameters do not reflect the bearing behaviour of MSW exactly as pointed out above. Nevertheless, conducting an analysis by means of Bishop's method may deliver a rough idea of the slope stability. However, the realistic stability still may be different.

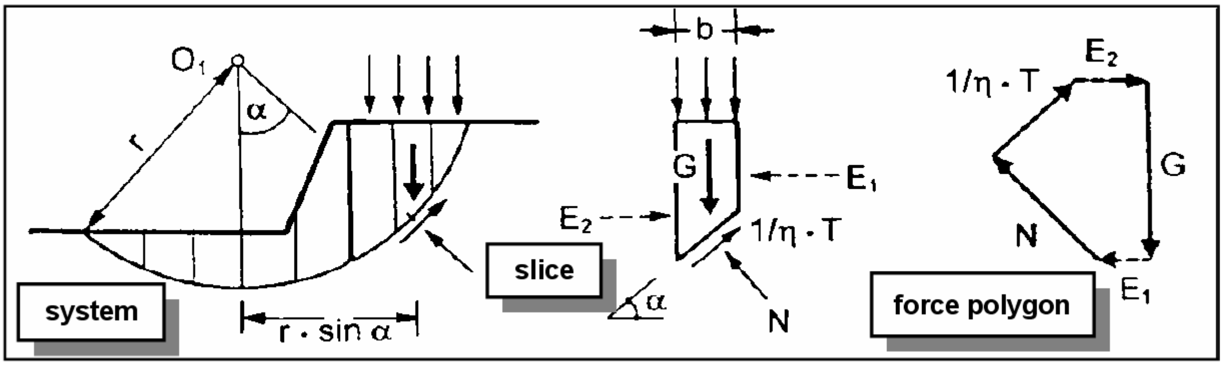

Figure 7: Bishop's method of slices

Advanced method I: Fibre-cohesion

In case of critical site conditions, advanced methods are strongly recommended. Those critical site conditions are:

- Extraordinary landfill height (> 30 m)
- Steep slopes (steeper than 1:3)
- Inclined subsurface (> 5 %)
- Soft subsoils (silk or softer)
- High water table (more than 20 % of total height, "bleeding" slopes)
- Sensitive location (e.g. distance to housing area <300m)
- Extraordinary loadings (e.g. earthquake)

Slope stability analysis accounting for fibre-cohesion (reinforcement effect) are based on a modification of well known geotechnical stability analysis models such as the Bishop's slip circle method or Janbu's sliding block method.

Shear law $T = N \cdot \tan\varphi + c \cdot l + \boldsymbol{\tau(z\alpha)}$

Fibre-cohesion $\tau(z_\alpha) = z \cdot a_\zeta \cdot \sin(1.5 \cdot \alpha)$

where:

tensile stress $z = \sigma'_v \cdot \tan\zeta$ (limit $z < z_{max}$)

normal stress $\sigma'_v = G/b$ (normal to main fibre direction)

transmission factor $a_\zeta = 0.7 - 1.1$

The advanced method differs from common method by the term of **$\tau(z\alpha)$,** which is 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:

$$T = \frac{G \cdot \tan\varphi + c \cdot b + \mathbf{G \cdot \tan\zeta \cdot a_\zeta \cdot \sin(1{,}5 \cdot \alpha)}}{1/\eta \cdot \sin\alpha \cdot \tan\varphi + \cos\alpha}$$

All added terms are indicated by bold letters. The extended shear law can be implemented in common computer-based calculation programs. Similar to common methods stability calculation is based on effective stress. Figure 8 illustrates the result of a stability analysis utilizing the introduced advanced method. Along the bottom of the slices the activated shear resistance is drawn. The analysis describes the Leuwigajah dumpsite failure, which happened in February 2005 in Bandung (Indonesia). The sliding figure corresponds to the shape of failure as it was observed on site (KÖLSCH et al., 2005**)**. The green line indicates the leachate head, which was estimated to a maximum of 15 m on top of the landfill base corresponding with pore water pressure of up to 150 kPa.

Figure 9 displays the same case modelled according to conventional methods. The overall factor of safety is much lower, because the shear resistance of fibres have not been considered. Even a higher value for the friction (φ = 30° instead of 20°) did not compensate the fibre cohesion. The overall factor of safety amounts to η = 0.54. The same sliding figure calculated by the advanced method shows a factor of safety of η = 1.28. However, the sliding figure found in conventional calculation does not match the real failure situation.

Figures 8 and 9 allow comparison of the results of the advanced method to the common method. Obviously the sliding figure is much larger due to the fact, that the waste generates a huge shear resistance based on reinforcement. Therefore, the part of the sliding figure crossing the waste tends to become small versus the part crossing the weaker subsoil (in this case: the soft clay subsoil). The bearing behaviour of this slope is completely different from what it seems to be when modelled by common methods. Usually, the overall stability is higher; however the geotechnical assessment may lead to different results. The most important part of the landfill moves towards the centre away from the crest of the slope. The landfill operator may avoid placing soft or wet waste (sludge) around those landfill sectors. Furthermore, the subsoil conditions are getting more important.

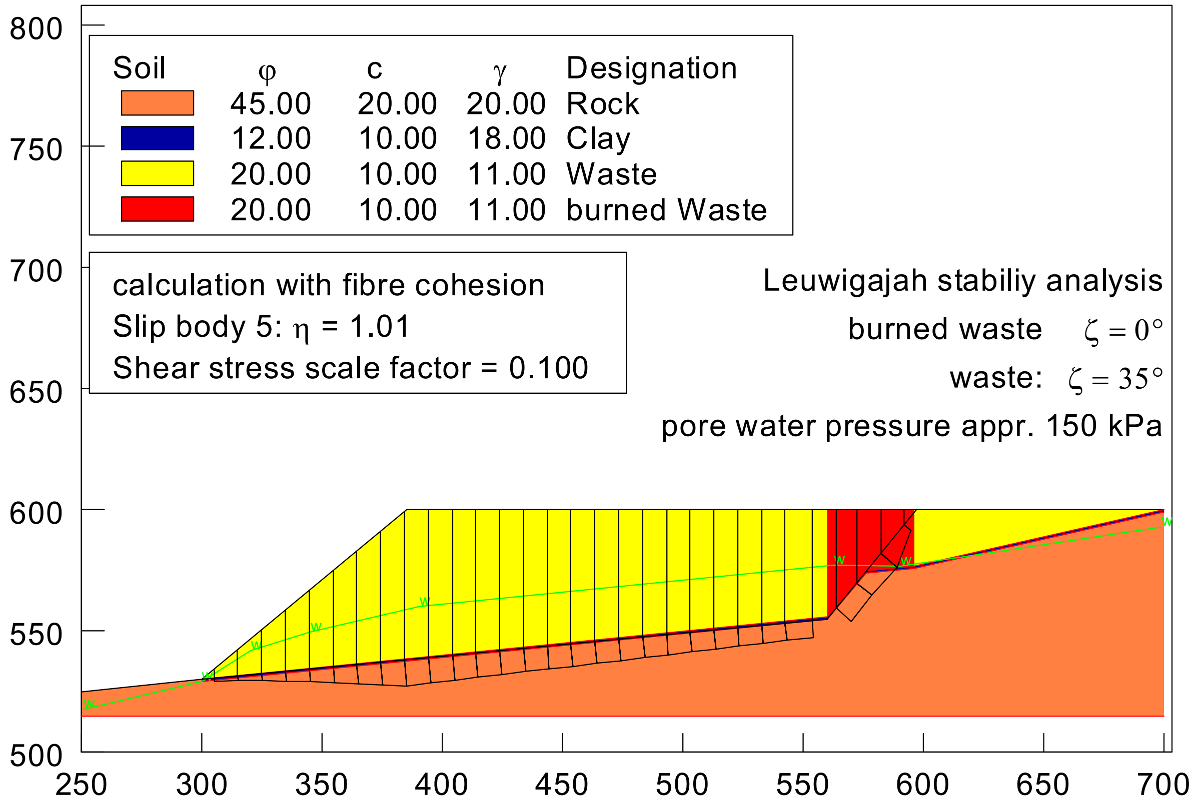

Figure 8: Stability analysis according to the advanced method of fibre-cohesion

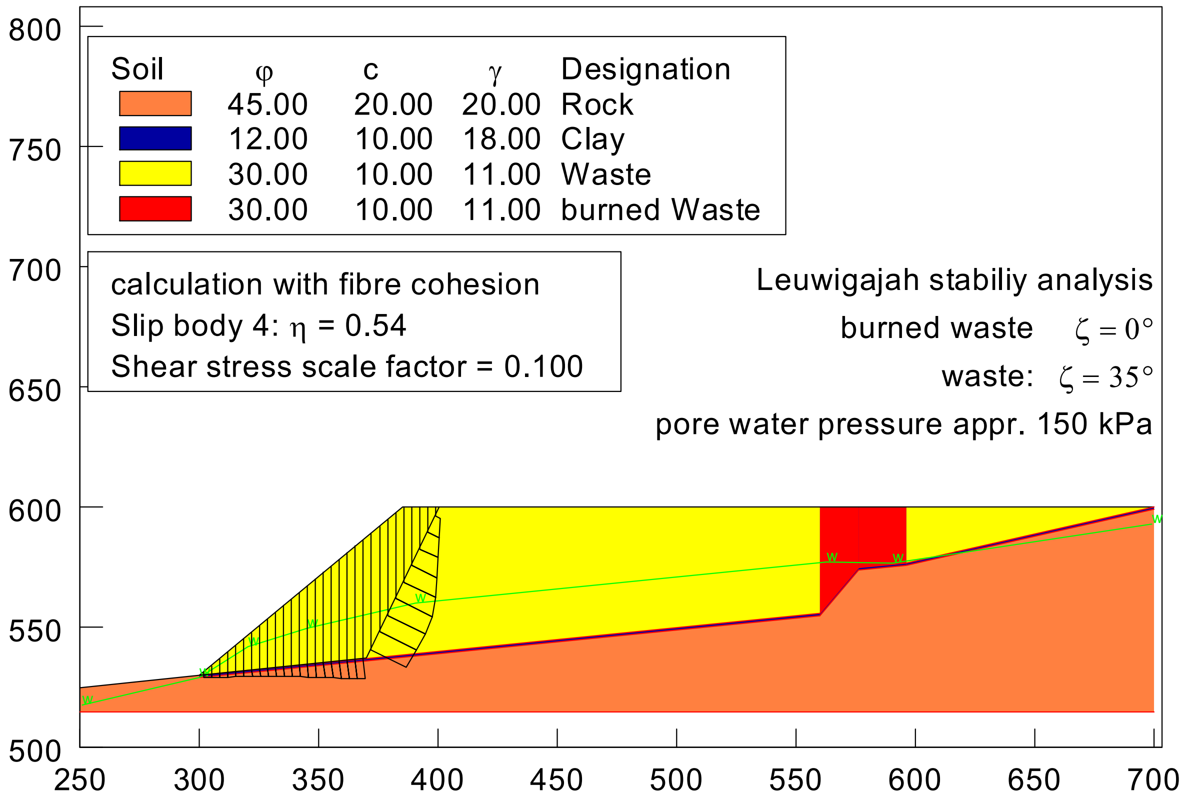

Figure 9: Stability analysis according to the common method

Advanced method II: Deformation dependent shear parameters
The utilization of the deformation dependent shear parameters requires higher sophisticated calculation and modelling methods. In order to determine the shear resistance at one certain point of the landfill, it is necessary to know about the vertical deformation. There are basically two options to determine the deformation:

- Settlement measuring on top, inside and on the base of the landfill
- Numerical modelling of the landfill deformation

As soon as the deformation rate of the landfill is determined, the shear parameters can be directed to the various locations along a sliding figure according to the numbers in Table 1 or as determined in laboratory triaxial testing results. The calculation procedure is similar to common geotechnical methods.

4 Geotechnical Consequences

4.1 Major Geotechnical Problems

Since the 1970s, geotechnical handling of landfills has been improved in Western countries. 30 years of experience in landfill geotechnics helped identifying the major geotechnical problems. Being aware of those problems enables delivering basic rules of proper landfill operation, which may help to avoid the worst problems. There are two major problems for landfill stability:

- water table inside the landfill
- landfill fires

Water table inside the landfill is the most critical factor in terms of landfill stability, because it reduces effective normal stress and shear resistance, respectively. All measures of landfill operation should aim on keeping the water table low. Regarding the landfill construction, the drainage system is the most important construction element. A drainage system should consist at least of a layer of well permeable drainage material such as gravel or sand. The efficiency of the drainage system can be improved by installing drainage pipes to collect the leachate.

A leachate collection system does not help very much if the water cannot percolate through the waste. To sustain a proper percolation, barrier layers inside the landfill should be avoided, generally. In some places a so called “daily earth cover” is required by regulations. It is important to construct those layers in a way which does not lead to barriers. Either well permeable soil materials should be used or the intermediate cover should be replaced or destructed prior to placing waste on top.

Concerning the waste density, it is important to understand, that a high density creates a high normal stress resulting in high shear resistance. The holding forces usually increase quicker than the driving forces, which are generated by high waste density. In terms of water percolation, a higher density may result in less permeability. On the other hand, less permeability on top of a dumping area reduces the penetration of water due to the fact that surface run-off and evaporation increases. Subsequently, a higher waste density maintains a proper water balance inside the landfill.

Landfill fires are another significant problem. Landfill fires contributed to one of the deadliest landfill failures at Leuwigajah dumpsite (Bandung/Indonesia) in February 2005 (see Photo 12). Landfill fires destruct the reinforcement particles (synthetics, paper) and significantly reduce the shear strength.

Photo 12:
Landfill fire at
Leuwigajah dumpsite

Photo: Hansjoerg Oeltzschner, Bachern/Woerthsee, Germany

4.2 Proper Operation

Taking those major problems into account, a number of basic principles and suggestions can be expressed. Waste dumping should aim on high density. Compacting waste by crawlers is generally insufficient. Whenever possible, compactors should be used to achieve a proper waste density. A number of problems can be avoided or at least minimized by good compaction.

Water management is an extremely important task especially in countries with high and non-uniform precipitation. Some basic procedures should be taken into account:

- Surface water and water penetrating the landfill from surrounding areas should be collected and directed away from the waste area.
- However, it can never be avoided, that water infiltrates the landfill and generates leachate. In any case, leachate percolates through the landfill. The more isotropic the landfill body is, the better it is to maintain proper percolation. Any kinds of barriers and non-uniform dumping areas should be avoided. This basic requirement applies also to Daily Earth Cover.
- At the landfill base, a dam up of leachate needs to be avoided. A proper drainage and leachate collection is essential. In case, the drainage system consists of drainage pipes, the pipes need to be maintained frequently by cleaning.

Landfill fires are absolutely unacceptable and must be set off immediately.

4.3 Geotechnical Emergency Measures

Due to insufficient design and construction or due to improper operation, a landfill may face critical geotechnical performance. There is a set of parameters which may indicate geotechnical problems. Cracks in covered areas close to the slope crest, horizontal displacements at the toe of the slope, vertical movement in front of the slope, local slope failures, inaccessible dumping areas, where mobile equipment lose in to the axes and other effects may show up. In those cases, emergency measures may help to avoid larger problems or disasters.

The principal measures should aim on bringing the water table inside the landfill down. Extraordinary drainage measures should be conducted, wherever applicable. Pumping in vertical wells, peripheral drainage trenches or pipes, immediate temporary cover, slope profiling to increase the surface run-off and similar measures are useful.

An immediate detailed stability analysis is strongly recommended to understand the reasons of the stability problems. Construction measures like bottom dams and the decreasing of slope angles by means of mining are very popular, but generally useless. In some cases, it may even be better to place additional waste in specific areas to increase normal stress and shear resistance. A stability analysis, only, provides the required information.

4.4 Local Specifics

Tropical countries face the heaviest problems concerning the points described above. Waste disposal in open dumpsites and landfills is very difficult primarily due to high, non-uniform precipitation of up to 2000 mm/year and 50 mm/h. At tropical landfill sites an extraordinary sensitivity versus water balance problems is required. However, locally well adapted disposal methods are still not available. Presently, it is clear that any kind of water movement towards the landfill is undesired. Leachate collection is strictly required and leachate circulation should be used very carefully only in dry season. Different operation in wet and dry season is recommended focussing on minimizing open dumping area in wet season. Suspending and covering parts of the landfill may help.

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