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Stability and barrier systems of municipal waste deposits

Systèmes de stabilité et de barrière des dépôts de déchets municipaux

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ABSTRACT: The paper underlines that an appropriate pre-treatment of waste is crucial to avoid the passing-on of environmental impacts of today's landfills to future generations. Morover, multi-barrier systems are recommended, especially in case of hazardous waste. For geotechnical stability analyses of waste deposits a compatibility investigation of the sometimes fundamentally different shear stress-strain behavior of waste and subsoil is recommended. Horizontal barriers commonly require composite liner systems, unless pre-treated or mono-waste of low risk potential is deposed. Assumptions for risk analyses are presented in this paper.

RÉSUMÉ: Le document souligne qu'un prétraitement approprié des déchets est essentiel pour éviter que les impacts environnementaux des décharges d'aujourd'hui sur l'environnement soient répercutés sur les générations futures. De plus, les systèmes à barrières multiples sont recommandés, en particulier, en cas de déchets dangereux. Pour les analyses géotechniques de la stabilité des dépôts de déchets, une étude de compatibilité du comportement contrainte-déformation, parfois très différente, des déchets et du sous-sol est recommandée. Les barrières horizontales nécessitent généralement des systèmes de doublure en composite, à moins que des déchets pré-traités ou des déchets simples présentant un potentiel de risque faible ne soient déposés. Les hypothèses pour les analyses de risque sont présentées dans ce document.

Keywords: Environmental geotechnics; landfill engineering; waste deposits; waste containment; waste stability

1 MULTI-BARRIER SYSTEMS

1.1 Interaction of barriers

Disposal facilities of municipal/household waste, industrial waste and especially of hazardous waste should be designed and constructed according to the "multi-barrier system". This term originates from nuclear engineering and originally defines a security system consisting of several protective measures ("barriers" which act independently from each other). It was then taken over and extended in the waste disposal terminology (Stief, 1996) and has been widely used in Germany and Austria since. The costs for a waste deposit decrease with degree of waste pre-treatment.

The multi-barrier concept comprises natural and man-made (“technical”) barriers. In the case of waste deposits above ground, these barriers include (Fig. 1):

- Natural barrier (“geological” barrier), incorporating proper site characteristics from a geotechnical and hydrological point of view;
- Horizontal barrier (bottom liner and drainage system);
- Capping barrier (cover and/or liner and drainage system);
- Vertical barrier (cut-off walls) plus inner groundwater lowering – not obligatory.
- In a broader sense, “multi-barrier systems” also include the deposit and the waste itself. The pre-treatment of the waste and the operation technology of the disposal facility therefore play a significant role within the framework of a safe, well-managed deposit.

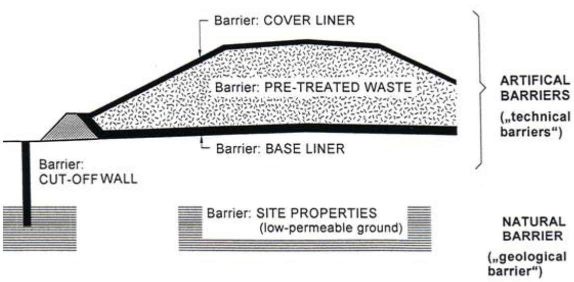

Figure 1 The multi-barrier system of a waste deposit

Consequently, the Austrian regulations contain rather stringent limit values for old and new waste deposits. This refers also to the quality of liner and drainage systems which could be improved and adapted to the state of the art within a legal transition period.

1.2 Natural versus technical barriers

The interaction of natural and artificial barriers determines the safety and the residual risk with regard to contaminant emissions from a waste deposit and should, therefore, play an essential role in siting. Sites which are only partly suitable, from a geological-hydrological point of view, can be significantly improved by appropriate construction measures, which is an important factor considering other evaluation criteria. A “technically neutral” evaluation, i.e. without specific consideration of technical, protective measures mostly leads to negative results, hence preventing the construction of needed disposal facilities. Subsequently, waste then continues, to a great part, to be “disposed off” in an unprofessional or even criminal way. Therefore, the environmental impact assessment or environmental compatibility analysis of a certain waste disposal site should always weigh the effects of the two possibilities: a so-called “zero-solution” in the entire region (with insufficient waste management) and an engineered waste disposal facility.

Referring to the natural (geological) barrier, different expert opinions do exist, and consequently also diverging national or even regional regulations. The discrepancy is mostly based on different “philosophies” of geologists (who want to rely only on nature) and geotechnical engineers (who also rely on the capacity of modern technologies). A highly engineered fill of clay or stabilised soil, executed under strict site supervision, certainly provides a sub-grade with a higher barrier effect than natural ground which always exhibits heterogeneity, discontinuities, etc. Therefore, Austrian regulations allow in case of insufficient geological barriers a substitution with multi-layered clay fills.

The required thickness of a “geological barrier” or its technical substitute varies between 1 m to 7 m depending on its permeability, on the waste properties, on the liner system of the landfill (e.g. single or double composite liner system), and on national regulations. Austrian governmental regulations also consider the permittivity $\psi = k/d$ of the ground which permits the following variation of the horizontal barrier properties:

- thickness $d \geq 5$m with $k \leq 10^{-7}$ m/s
- or $d \geq 3$m with $k \leq 10^{-8}$ m/s ($d \geq 1$m with $k \leq 10^{-9}$ m/s only in exceptional cases)

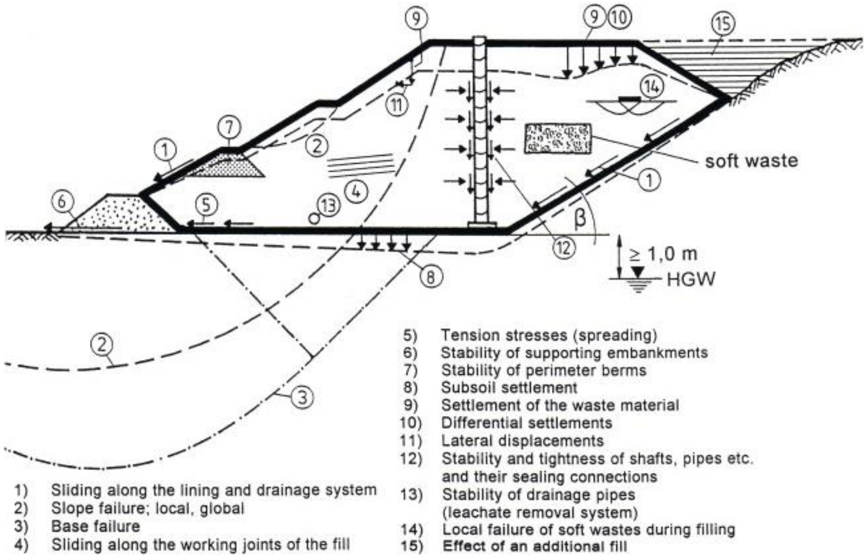

Figure 2 Stability and deformation problems which have to be considered for design, construction, operation, aftercare and monitoring of a waste deposit.

Thinner barriers are not permissible, at least not for natural subsoil which always exhibits a scatter of parameters which is locally uncertain, even if it is described as a so-called homogeneous ground. But modifications are possible depending on the mineral composition of the barrier which also has a strong influence on the efficiency of the natural or artificial barrier.

2 STABILITY OF LANDFILLS

"Landfill stability" in the widest sense comprises geotechnical, physical, chemical and hydrological aspects. Accordingly, a landfill may be considered „stable" when its contents do no longer pose (significant) risks to human health or the environment. However, widely/internationally accepted definitions of „landfill stability" and „final storage quality" are not available. Therefore, the following chapter focuses only on the geotechnical stability of landfills.

Waste disposal facilities may be conventional landfills, structural containments, or deposits in underground spacings.

Conventional pit-landfills can be best "hidden" in the landscape but require extensive drainage/pumping to remove the leachate. A natural drainage is not possible there which results in a higher risk in case of defects in the drainage or barrier system. Leaks in a (conventional) bottom liner system or leakages from there may be localised in sectors, but not at the exact point. A repair of the bottom liner is basically only possible after waste removal. Consequently, landfilling of excavation pits creates in many cases the contaminated sites of the future. Therefore, in Austrian regulations only waste piles and slope/or canyon fills are permitted for new facilities. A natural drainage of the bottom and capping liner systems must be available in order to minimise operation costs, long-term risks and maintenance or aftercare, respectively. As a compromise, a partial filling of larger excavation pits can be tolerated if the deposit exhibits the form of a slope fill, or if pit fills are situated near the crown of slopes where a natural drainage of leachate is possible.

Legal exceptions from this regulation are the adaptation of old facilities to the present state-of-the-art and deposits where practically no leachate arrives at the bottom liner/drainage system – both exceptions in combination with high quality natural and technical barriers.

Figure 2 gives an overview of several geotechnical aspects which have to be considered for the design, construction, operation, and aftercare of a waste deposit. The main problems with regard to geomechanics are large differential settlements in the base of the waste deposit and slope stability. Consequently, several national regulations basically exclude weak soils or unstable slopes as possible sites for waste disposal facilities – which may be too stringent. On the other hand, they recommend "standard"–values for calculatory waste parameters, assuming stress-strain compatibility – which in most cases does not exist.

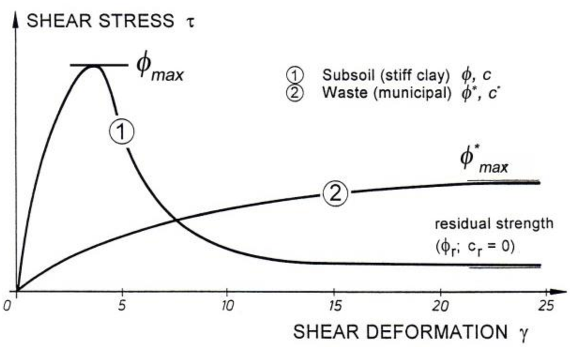

Figure 3 Shear strength – strain diagrams for municipal waste and stiff clayey soil. Schematic: completely different, strain-dependent mobilization of the shear resistance.

Slope stability analyses have to take into account that municipal solid waste and soil have completely different shear stress–strain properties – especially if the subsoil consists of stiff clays or silts with a low residual shear strength, Φ_r, as indicated in Fig. 3. Municipal household waste requires large shear deformations until the entire shear strength is mobilised. Unlike stiff soils, MHW does not exhibit a clear fracture. Therefore, the friction angle is a fictitious value, symbolised by Φ^*. In contrary, the soil reaches its peak strength, Φ_{max}, already at relatively small deformations, and further movements cause a decrease to Φ_r. A similar discrepancy refers to the cohesion: Large shear deformations in the soil reduce the cohesion from c to finally $c_r = 0$, whereas they still mobilise an increasing fictitious cohesion, c^*, in the municipal waste. Consequently, slope stability analyses of waste deposits have to consider the compatibility of waste and subsoil deformations, especially in case of slope fills (Fig. 4). For slope stability and ground analyses the following shear criterion has proved suitable:

- municipal waste: $\Phi_{calc} < \Phi^*_{max}$, $c_{calc} < c^*_{max}$;
- subsoil (clay barrier): $\Phi_r < \Phi_{calc} < \Phi_{max}$, $c_{calc} \geq c_r = 0$

The different shear stress-strain behaviour of municipal waste and subsoil (or clay liners) influences not only the safety factor but also the shape and location of the most critical slide surface. Fig. 5 shows the total shear resistance $\sum\tau_i \cdot l_i$ along the slide surfaces a, b, c of Fig. 4, and it illustrates a dominating influence of the subsoil's parameters which is usual in case of a very low residual shear strength of cohesive ground.

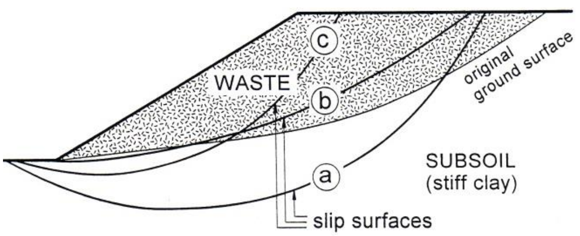

Figure 4 Slope failure investigation of a slope fill with relevant slip surfaces running through the waste deposit (municipal waste) and the subsoil (stiff clay). Slip surfaces a, b, and c assumed as examples.

Especially critical is a progressive slope failure starting from the toe zone of a landfill, e.g. in a locally overstressed zone of low (residual) shear strength. Fig. 6 illustrates the progressive propagating of the failure towards the crown, whereby the shear stress-strain behaviour in the points A, B, C differs significantly: In A large shear deformations may have led already to the residual value Φ_r, whilst B has just reached its maximum resistance, and C has mobilised only a small part of its full shear resistance.

In case of landfills with steep slopes and/or subsoil with high shear strength, slope failures usually start on the crown of the waste deposit. Horizontal tensile stresses in the upper zone cause vertical cracks there, thus mobilising to a high degree the shear strength of the waste.

The consequences for slope stability analyses, risk assessment and design are:

• Low-permeable ground which is advantageous for waste disposal sites exhibits in many cases a low residual shear strength and the tendency to progressive failure. Therefore, a detailed investigation of the shear parameters is essential, especially the determination of Φr.

• The shear properties of municipal waste cannot be described by "constants" or standardised parameters, and they are therefore not well suited for being included in regulations. Stability analyses should be based at first on a deformation assessment and allowable deformations respectively.

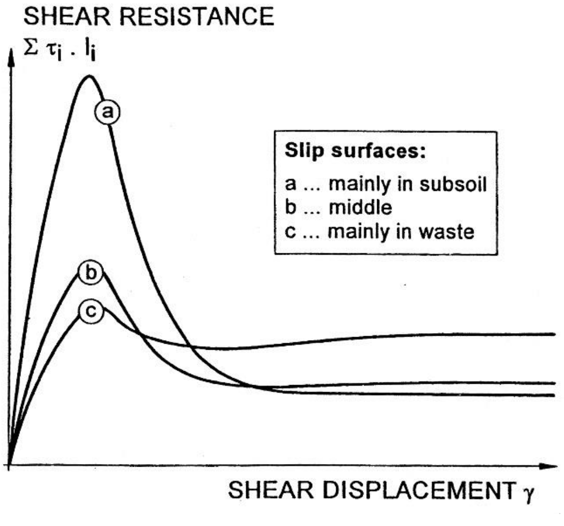

Figure 5 Shear resistance along the slip surfaces a, b and c in Fig. 4, based on the τ - γ - diagrams of Fig. 3.

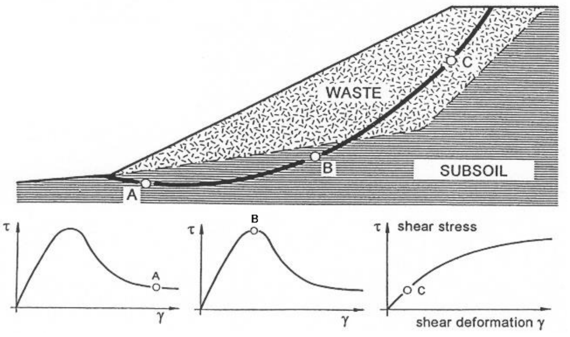

Figure 6 Shear strength-strain diagrams: Completely different mobilisation of the shear resistance in waste and subsoil.

3 BOTTOM LINER SYSTEM

The bottom liner usually represents the most important technical component of the multiple-barrier system. Therefore, it should consist at least of two different sealing materials to achieve a high, durable, and multi-efficient barrier effect against contaminant migration. This is achieved by composite liner systems. So-called mono systems, consisting only of one material (e.g. geosynthetics or recycling products) should be limited to waste deposits with a low risk potential.

Composite liner systems may consist of clayey soils ("mineral liners") and/or geosynthetics, asphalt, recycling material, chemically improved soil, metals, etc. Most regulations for municipal solid waste and for hazardous waste prescribe composite liner systems based on clay liners and geosynthetics, also incorporating a proper drainage (leachate collection and removal) system. But the possibility of alternatives should be kept open to encourage further developments.

Innovative systems should exhibit at least the same efficiency as conventional systems, hence, a technical equivalency must be proved. To evaluate this, risk analyses are necessary, also including the properties of the waste and the subsoil, whereby the durability of the components plays an essential role.

Table 1 Assumption for a risk analysis evaluating the base liner of a waste deposit.

Phase	Period (years)	Efficiency of the barrier				
		Subsoil/subgrade		Liner and drainage system		
		geological barrier	technical barrier	clay liner, mineral liner	geosyn-thetics	drainage systems
Operation (filling of waste)	0 - 25	++	++	++	++	++
Operation and/or aftercare	25 - 50	++	++	++	++	++, + [1)]
Aftercare	50 - 100	++	++	++	++, + [1)]	+
Final state [2)]	100 -	++	++	++, (+) [1)]	+, 0 [1)]	(+), 0

[1)] Depending on mechanical, chemo-physical and biological Impact, construction, quality of installation and maintenance (e.g. flushability of the drain pipes etc.)
[2)] No further monitoring, gas and leachate collection

++ intact, in full working order
\+ intact, but probably impaired
0 no longer in working order

Table 1 contains some assumptions referring to clayey and geosynthetic liners. The values actually depend very much on the usage, the structure, the materials, and the installation quality of the liner and drainage system. For instance, geomembranes placed between clay liners, will probably still be intact even after 100 to 200 years. Mono-systems consisting only of geosynthetics make a thinner structure possible but, on the other hand, exhibit a shorter life-time than composite systems.

4 CONCLUSIONS

Concerning the design and operation of new landfills, it should be emphasized that a “100%-barrier efficiency” cannot be achieved, even with highly engineered waste disposal facilities, unless the waste exhibits a very low risk potential or is properly pre-treated. Hence, waste separation (already during collection) and pre-treatment should have priority over complicated containment concepts.

Accordingly, waste should be deposited only if the total organic carbon (TOC) is 5% at the maximum (or the lower caloric value LCV $\leq$ 6000 kJ/kg). Otherwise multi-barrier systems are required wherby the compatibility of different shear stress-strain behaviour of waste and subsoil has to be considered.

With regard to the design of new waste disposal facilities, reasonable regulations are to be favoured, which require negligible impact for a prescribed period of time. This aftercare period should be at least 30 years after closure of the landfill, depending on the results of monitoring (landfill gas, leachate, settlements, slope stability, etc.).

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