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Sustainable Landfill and Final Storage Quality

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Abstract
Widely accepted definitions of 'landfill stability' and 'final storage quality' are not available. These terms are very often used in discussions about sustainable landfill. Consequently there is also no shared notion of sustainable landfill or final storage quality. In a Dutch sustainable landfill project it was proposed that: 'a landfill is stable when the undisturbed contents do no longer pose a threat to the environment in any way'. Clearly the potential threat does not only depend on the landfill but also on the environment. This paper argues that the method used to establish the acceptance criteria for waste on landfills in the Annex II of the European Landfill Directive provides a starting point for the evaluation of landfill sustainability and the development of a risk assessment method.

1 Introduction
The most widely adopted definition of sustainability is the one proposed by the Bruntland Committee: 'sustainability ….. a form of sustainable development which meets the needs of the present without compromising the ability of future generations to meet their own needs'. In waste management sustainability is often explained as: 'solve your environmental problems within your own generation'. One generation is most widely understood as approximately 30 years.

With respect to landfills very often terms as stability, completion, end-point and threat to the environment are used together in discussions about sustainability.

A selection of definitions is:

- SWANA Stability Subcommittee (Barlaz, 2005): A landfill is 'functionally stable' when the waste mass, post-closure, does not pose a threat to human health and the environment. This condition must be assessed in consideration of leachate quality and quantity; gas composition and production; cover, side-slope and liner design; site geology and hydrogeology; climate; potential receiving bodies, ecosystems and human exposure; and other factors deemed relevant on a site-specific basis.

- Anglo-Welsh Environment Agency (Environment Agency, 2005): Completion is defined as that point at which a landfill has stabilised physically, chemically and biologically to such a degree that the undisturbed contents of the site are unlikely to pose a pollution risk in the landfill's environmental setting. At completion, active aftercare pollution controls (e.g. leachate management and gas management) and monitoring systems are no longer required.
- DHI (Hjelmar, 2005): Waste at final storage quality provides a situation where active environmental protection measures at the landfill are no longer necessary and the leachate is acceptable in the surrounding environment.
- Technical University of Hamburg (Stegmann, 2003): The aftercare phase may end when the emission potential is that low that the actual emissions do not harm the environment.

All the relevant aspects come together at completion. Completion of a landfill is the moment at which the landfill operator is discharged from its aftercare obligation. It is in the interest of the landfill operator to have a clear protocol how completion is assessed and which requirements have to be met. In order to avoid transferring environmental problems to the next generation it should be environmentally safe to abandon the landfill at completion. Although the different definitions use slightly different wording, there seems to be a general consent that a sustainable landfill or a landfill at final storage quality is a landfill that within a limited period of time reaches a state where the undisturbed contents are no threat to human health and the environment. It is important to note that this is completely in line with the intention of European waste legislation.

2 Regulatory framework in Europe

Reaching final storage quality is implicitly assumed in many landfill regulations. Strategies and means to achieve it have not yet been included in landfill regulations and guidelines (Hjelmar, 2005). The European Commission has recently emphasized that the guiding principle for waste regulation is to guarantee the protection of the environment and of human health. In the proposals for the Thematic Strategy on the prevention and recycling of waste (CEC, 2005a) and the Waste Framework Directive (CEC, 2005b) it is expressed to give more attention to risk assessment and life cycle thinking.

Article 13(d) of the European Landfill Directive (CEC, 1999) states: for as long as the competent authority considers that a landfill is likely to cause a hazard to the environment, the operator of the site shall be responsible for monitoring and analysing landfill gas and leachate and groundwater regime in the vicinity of the site. Consequently aftercare can not be ended, or in other words landfill completion can not be agreed upon, until the competent authority can be convinced the landfill is no longer causing a hazard.

Article 2(e) of the European Landfill Directive (CEC, 1999) states: 'inert waste' means waste that does not adversely affect other matter with which it comes into

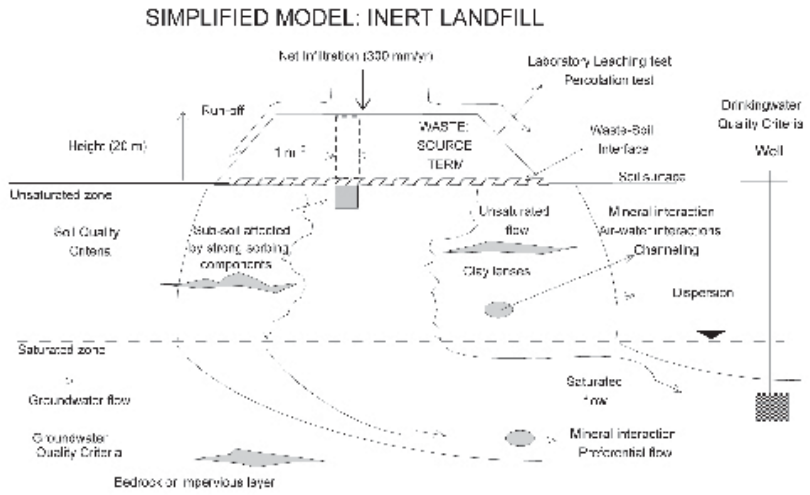


Fig. 1: Aspects for the establishment of acceptance criteria for inert waste on landfills.

contact in a way likely to give rise to environmental pollution or harm human health. The total leachability and pollutant content of the waste and the ecotoxicity of the leachate must be insignificant, and in particular not endanger the quality of surface water and/or groundwater.

The European acceptance criteria for inert waste on landfills are leaching limit values (CEC, 2003b). They are based on not exceeding drinking water standards in the groundwater (Hjelmar, 2001) at a point of compliance near the landfill taking into consideration all the processes below the landfill (Figure 1).

The European Landfill Directive does not require isolation and aftercare for landfills for inert waste. In combination with the statement that inert waste does not give rise to environmental pollution or harms human health, this implies that the emission associated with the leaching limit values is considered acceptable. It has indirectly defined final storage quality. When discussing definitions for sustainable landfill or final storage quality, it seems necessary to consider the conditions specified for inert waste and risk assessment.

It is also important to note articles 12(b) of the Landfill Directive and 1.1.1.b of the Annex II. Article 12(b) requires that data shall be gathered with the purpose of increasing the knowledge on waste behaviour in landfills. Article 1.1.1.b states that basic information is required for each type of waste for understanding the behaviour of waste in landfills. The gathering and reporting is usually taken care of in national regulations. There is however little evidence of actions to actually use this information for the purpose of increasing knowledge on and understand-

ing of waste behaviour in landfills.

3 Landfill process stimulation

Throughout the world various methods are proposed to stimulate landfill processes in order to accelerate achievement of final storage quality. In the end the goal is the same: to achieve completion of the landfill. Most of these methods relate to pre-treatment or bioreactor type of processes for biodegradable organic waste. During a workshop of the InterContinental Landfill Research Symposium the idea was proposed that several types of waste can be processed in different landfill concepts (Scharff, 2006). When most of the organic carbon has been



degraded the behaviour of the landfill body converges to the behaviour of an inorganic waste landfill (Mathlener, 2006). The same applies to (suitable types of) hazardous waste after immobilisation or cement stabilisation. In other words: for all types of waste on the road to completion it seems inevitable to 'pass through' a stage that is comparable to an inorganic waste landfill.

Fig. 2: Waste types and methods to achieve completion.

4 Inorganic waste landfill

Amounts leached from an inorganic waste pilot project (Equifill) were derived by combining leachate quality data with leachate quantity data. In Table 1 these amounts are compared to limit values for waste acceptable at landfills for inert, non-hazardous and hazardous waste expressed in the Annex II of the EU Landfill Directive. The Annex II states two L/S ratios for which limit values were determined (L/S = 2 and L/S = 10). As the L/S ratio of the pilot cell is 0.9 actual leachate quality is compared to Annex II limit values at L/S = 2.

However results obtained at L/S = 0.9 and limit values obtained at L/S = 2 are

Tab. 1: Leaching data Equifill and limit values EU Landfill Directive Annex II.

Parameter	Equifill L/S=0.9 mg/kg	Column L/S=2 mg/kg	Inert L/S=2 mg/kg	Non-hazardous L/S=2 mg/kg	Hazardous L/S=2 mg/kg
As	0.01	0.012	0.1	0.4	6
Ba	0.17	0.11	7.0	30	100
Cd	0.001	0.02	0.03	0.6	3
Cl	901	3645	550	10,000	17,000
Cr	0.01	0.004	0.2	4	25
Cu	0.0005	0.003	0.9	25	50
DOC	105	179	240	380	480
Mo	0.01	0.014	0.3	5	20
Ni	0.03	0.1	0.2	5	20
Pb	0.01	0.06	0.2	5	25
SO_4	1144	3629	560	10,000	25,000
Sb	0.007	0.008	0.02	0.2	2
Se	0.014	0.011	0.06	0.3	4
Zn	0.018	0.5	2	25	90
F	0.220	-	4	60	200
TDS*	-	-	2,500	40,000	70,000
NH_4**	65	?	?	?	?
NO_3**	?	?	100-200	?	?

* The value for TDS (total dissolved solids) can be used alternatively to the values for sulphate and chloride (CEC, 2003).

** Annex II does not include nitrogen limit values. They will however be introduced by the future Groundwater Directive.

rather hard to compare. Therefore the leachate quality obtained by column leaching tests at L/S = 2 is also given in Table 1. The obtained leaching characteristics with column leaching tests for Annex II components enable better understanding and comparison of leaching behaviour of the pilot cell.

The Equifill leachate quality (L/S = 0.9) shows that most components do not exceed EU Landfill Directive limit values for waste acceptable at landfills for inert wastes so far. At first glance chloride and sulphate could be indicated as non complying components. The Annex II states that values for TDS (total dissolved solids) can be used alternatively to the values for chloride and sulphate. Since Ca leaching of the waste mixture amounts to 2,000 mg/kg at L/S = 2 it can be expected that TDS will not provide a solution for non compliance with the Annex II criteria. To achieve compliance for these components, two routes can be followed. Adequate pre-treatment measures like flushing of salts could be taken and stricter acceptance criteria must be set in order to comply with Annex II limit values

for landfills accepting inert wastes. The second route could be based on a site specific risk assessment of the landfill. In this approach, the local groundwater conditions are also taken into account. Exceptions can be made for chloride and sulphate concentrations in situations with relatively high background concentrations (e.g. brackish groundwater). When a risk assessment approach is taken, it can be argued that chloride and sulphate are irrelevant at the landfill site in question. The neighbouring Noordzeekanaal and the groundwater in the area of the pilot project are brackish and contain concentrations of chloride (2,500 to 5,000 mgCl/ l) and sulphate (500 to 700 mgSO_4/l) similar to the leachate (1,100 mgCl/ l and 1,300 mgSO_4/l).

Various sources (e.g. Krümpelbeck & Ehrig, 1999; Stegmann et al., 2003) indicate that nitrogen is a component that very often exceeds groundwater standards or surface water discharge standards for a very long time. The EU Landfill Directive Annex II does not include limit values for nitrogen. The future EU Groundwater Directive (CEC; 2003) will introduce the necessity to determine limit values for nitrogen for inert waste landfills. Applying the same methods that were used for the establishment of acceptance criteria for inert waste and the expected groundwater standard of 50 mgNO_3/l for drinking water, a limit value for nitrate can be calculated. It is expected (van der Sloot, 2005) that such a limit value at L/S = 2 will be between 100 and 200 mgNO_3/kg. At L/S = 0.9 the pilot project has released 65 mgNO_3/kg.

Column leaching tests provide additional information whether limit values will be exceeded when Equifill reaches L/S = 2 in time. Van Zomeren (2005) gives an overview of both column tests and full scale pilot results for some of the components. The paper discusses if both systems correspond and whether prediction of long term leaching behaviour can be described by column leaching tests. When Equifill leachate quality and leachate quality obtained by column testing are compared slight variations can be indicated. One must keep in mind that during a column batch test a large part of the waste packed in the column interacts with percolating water or leachate. The interaction between waste and percolating water or leachate within the pilot cell is smaller. Hence, variations between leaching tests and pilot scale can be explained by the differences in mobile or immobile fractions.

5 Developing a risk assessment approach

A risk assessment approach can define optimal design and operation in a given environment. Examples already exist in the European Landfill Directive:

- Annex I par. 3.4,
- Annex II par. 2.5 and
- Annex II the method for acceptance criteria.

There are a few limitations. The method to derive the acceptance criteria has assumed an average European soil, that does not widely occur, and that ground-

water can be used for drinking water. The method has also ignored the processes that occur in the landfill. During the operational phase leachate treatment and bottom liners prevent emissions. It could be considered acceptable that compliance is only due after closure of the landfill. In addition, site specific parameters (e.g. groundwater quality) need to be included in the risk assessment.

6 Modelling long term impact

Landfills have widely varying waste composition and are situated in widely varying conditions. Knowledge on waste-waste interaction has made it possible to model and predict the leaching of contaminants. A database/expert system is being developed to make this knowledge more accessible (www.leaching.net). In a Dutch sustainable landfill project for predominantly inorganic waste (Equifill), long-term leaching behaviour was compared with acceptance criteria. Only chloride and sulphate did not comply with the limit values. However, the brackish surface water and groundwater at this landfill contain concentrations of chloride and sulphate similar to the leachate. The groundwater is not suitable for drinking. In this case, it is obvious that drinking water standards are also not suitable to assess compliance.

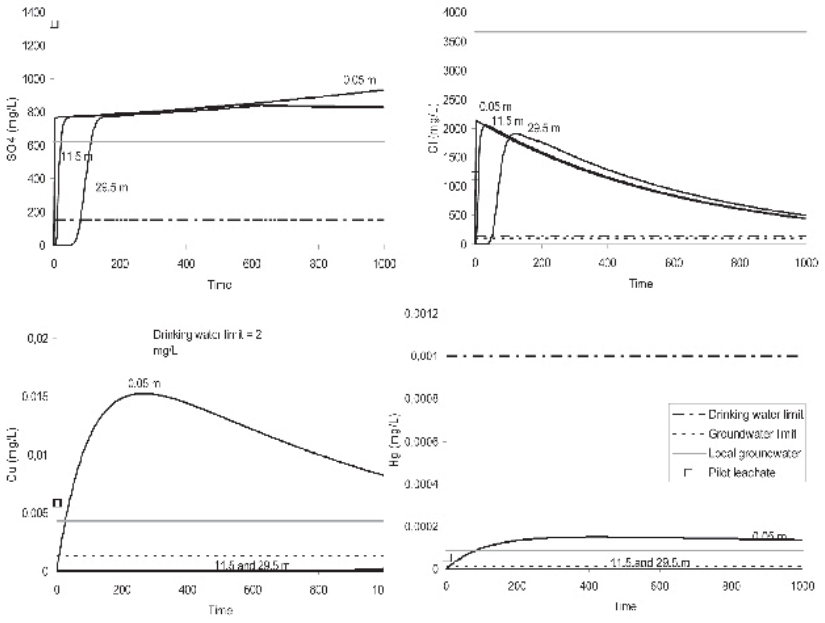


Fig. 3: Predicted emissions of Cl^-, SO_4^{2-}, Cu and Hg at 0.05m, 11.5m and 29.5m from the landfill as a function of time.

In this study, emissions are calculated as a function of time based on the measured source term of contaminants (Figure 3). The underlying soil (up to 30 m from the landfill) is able to bind contaminants by adsorption to iron oxides and solid organic matter. Solubility control by mineral phases is also a release controlling process. Thermodynamically consistent semi-empirical binding models have been used to predict the long-term impact of the landfill. The modelling results are presented in Figure 3. It can be seen that sulphate and chloride leachate concentrations are just above or significantly lower than the local groundwater concentrations, respectively. Cu and Hg concentrations are well within the required drinking water limits.

7 Conclusions

The example illustrates that 'stable situation' and 'final storage quality' are not aspects that can be defined entirely by means of absolute numbers. Acceptable limit values depend also on the local situation. A rigid definition of leaching limit values does not always coincide with a realistic impact assessment. In order to end aftercare the landfill operator needs to prove to the competent authority that the landfill no longer poses a threat to the environment. A list of limit values can only achieve this if large (possibly unattainable) safety margins are introduced. Landfill operators therefore need a risk assessment approach. They also need an approach that (unlike the Annex II) takes the entire landfill (cell) into account instead of just individual waste batches. Development of such an approach meets the goal set out in articles 12(b) of the Landfill Directive (increasing the knowledge on waste behaviour in landfills) and 1.1.1.b of the Annex II (understanding the behaviour of waste in landfills). Moreover, the approach should account for different soil conditions and groundwater standards as the site selection of landfills is an important aspect of sustainability. This can be achieved with an approach similar to the establishment of the acceptance criteria of the Annex II of the European Landfill Directive.

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