Theme lecture: Pollutants containment via passive barriers

Exposé sur le thème: Confinement des polluants par barrières passives

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ABSTRACT: After a short introduction of the main types of passive barriers today used for top, bottom and side landfill liners and polluted subsoil confinement, the paper describes the main features and new trends of compacted clay liners (CCL), geosynthetic clay liners (GCL) and cutoff slurry walls (SW) in relation to the design, construction and quality control in the short and long term. Some topical problems have then been discussed while looking at the main expected features of a passive barrier, such as low hydraulic conductivity, compatibility, durability, attenuation capacity and low diffusion-dispersion. These problems in particular concern the correct and reliable execution and interpretation of laboratory tests, the relative importance of different parameters for the evaluation of the barrier performance and the theoretical modelling of pollutant migration at the interface between the small scale of the barrier and the large scale of the aquifer. Finally, a comparison between prescriptive and performance design approaches has been attempted in order to try to obtain some useful indications on possible future developments in the field of regulations and recommendations in the light of the discussed modellings and parameters reliability.

RESUME: Après une brève introduction sur les principaux types de barrières passives utilisées aujourd'hui dans les systèmes d'ètanchéité des fonds, bord et couvertures des décharges et dans le confinement des sols contaminés, l'article décrit les principales caractéristiques et les nouvelles tendances dans l'utilisation de revêtements tels que l'argile compacté, les géosynthetiques et les parois moulées pour ce qui concerne le projet, la construction et le contrôle de qualité à court et à long terme. Quelques questions d'actualité sont traitées par la suite, se référant aux principales caractéristiques qu'une barrière passive doit garder, telles que basse conductivité hydraulique, compatibilité, durabilité, capacité d'atténuation et basses dispersion-diffusion. Ces problèmes concernent particulièrement la correcte et fiable exécution et interprétation des tests en laboratoire, l'importance relative des différent paramètres dans l'évaluation des performences de la barrière et la modélisation théorique de la migration des polluants à l'interface entre la barrière, qui est à petite échelle, et l'aquifère, à grande échelle. En conclusion, on tente une comparaison entre les approaches d'un projet qui donne des prescriptions et d'un projet qui garde aux performances, dans le but d'essayer d'obtenir quelques indications utiles sur les possibles futurs développements dans le domaine des règles et recommandations, à la lumière de la fiabilté des modélisations et des paramètres tratés dans l'article.

1. INTRODUCTION

One of the main contributions of geotechnics to topical environmental problems can be singled out in the field of the design and construction of passive barriers for pollutant containment.

The main advances in this field over the last 10 years can be listed as follows (Manassero et al., 1996): (1) setting up and optimisation of emplacement methods for compacted clay liners, leading on average to a field hydraulic conductivity reduction of 1 or 2 orders of magnitude in comparison to original compaction procedures adapted from structural embankments; (2) setting up and optimisation of execution techniques and backfillling mixtures for cutoff walls; (3) the use of composite liners and composite cutoff walls that results in a further reduction of the field hydraulic conductivity by about 1 - 2 orders of magnitude, at least in the short to medium terms (50 - 150 years) plus other significant advantages, in terms of landfill bottom drainage efficiency and improvement of mineral liner compatibility; (3) setting up and optimisation of suitability investigations and quality control procedures, in terms of laboratory and in situ tests and monitoring systems; (4) recognition of the importance of sorption dispersion and diffusion phenomena in relation to the global efficiency of the mineral barriers; and (5) the use of geosynthetic products with different functions within the different liners and barrier profiles.

The main types of passive barriers today employed for pollutant containment can be listed with reference to the cover, bottom and side systems:

- cover barriers can include compacted clay or mineral liners (CCL), geosynthetic clay liners (GCL), geomembranes, capillary barriers and composite barriers that result from the combination of the previously mentioned different types;
- the main types of bottom barriers for new landfills consist of compacted clay liners, geosynthetic clay liners, geomembranes and composite barriers; whereas indigenous, grouted and jet grouted barriers are the most common types for abandoned landfills and polluted sites. Tunnelling and microtunnelling techniques have also been proposed in the case of the very particular conditions of abandoned landfills, but to the author's knowledge real full scale applications have been very rare, if any, up to date;
- the main types of vertical side barriers or cutoff walls consist of slurry walls (SW); sheet and intersecting pile walls, concrete diaphragm walls; grouted and jet grouted curtains; soil-mix curtains, freezing curtains, reactive walls (which are something placed between passive barriers and clean up systems for polluted sites) and composite barriers made by combining some of the previous types.

Due to space constraints it has here been decided to concentrate on: (1) CCL; (2) GCL and, (3) SW. This choice has been made because of both their present worldwide diffusion and the potential of interesting developments in the future.

2. COMPACTED CLAY OR MINERAL LINERS

The various materials that can be used for CCL's are outlined in tab. 1 (Shackelford & Nelson, 1996). The first class of materials includes different combinations of naturally occurring soils, usually located in borrow pits near the disposal site.

A mixture of one or more constituent soils that are blended, or mixed together to form a new soil with the desired properties is referred to as a blended soil.

Table 1. Compacted clay (mineral) liners (adapted from Shackelford & Nelson, 1996)

MATERIALS	EXAMPLES
NATURAL SOILS (From borrow source)	Silts and clay Sands with significant fine content
BLENDED SOILS OR SOIL MIXTURES (From quarries)	Sand/attapulgite claay Sand/sodium bentonites Sand/calcium bentonites
AMENDED OR CHEMCALLY STABILIZED CLAY SOILS	Clay soil with attapulgite clay Clay soilwith bentonites Clay soil with cement Clay soil with fly ash Clay soil with lime Clay soil with organic modifiers Clay soil with polymers
MULTIMINERAL-MULTILAYER CLAY LINERS	Clay soil coupled with zeolithes Clay soil coupled with activated carbon Clay soil coupled with inorganic oxides Clay soil coupled with microbacteria cultivations

Amended or chemically stabilised soils may be required when the original fine grained soil presents an unacceptable large HC and/or is not compatible with the liquid waste or leachate that must be contained. Attapulgite and bentonite are usually employed for decreasing hydraulic conductivity (HC). Cement, fly-ash and lime can be used both to decrease HC and to increase strength; other positive effects such as precipitation of heavy metals due to an alkaline environment have also been mentioned in literature.

Organically modified clays, or organophilic-clays are natural clays where the inorganic interlayer exchangeable cations have been substituted by organic cations such as quaternary ammonium organic cations, benzyltriethyllammonium (BTEA) bromide or dodecyltrimethylammonium (DDTMA) bromide. This substitution enhances the ability of the clay to absorb organic chemicals (e.g. benzene, dichlorobenzene, perchloroethylene), as reported by Shackelford & Nelson (1996). Synthetically produced polymers (e.g. metacrilates, polyacrylammide, etc.) can be added to clay soils to decrease the HC via their dispersive capacity on clay particles.

In order to optimise features such as long term HC, high sorption capacity and long term chemical stability one of the new trends in mineral liner design considers the combination of different mineral layers with different functions (Bradl & Kliesh, 1997; Gouvenot & Raillard, 1997). Kaolinitic clays are usually used for inactive and low permeability layers, while organophilic bentonites, zeolithes, activated carbon, inorganic oxides and microbacteria cultivations are employed as active high sorption or degradation layers.

3. GEOSYNTHETIC CLAY LINERS

The use of GCL's can, in some cases, be a valid alternative to CCLs. However a series of delicate aspects must be carefully considered. These include: (1) the compatibility problems of sodium bentonites that form most CCL's, (2) possible wetting and drying sequences in the field, and (3) sorption capacity and sensitivity to potential mechanical damages due to the limited thickness of this kind of barrier. The problems of the general stability of the waste body must also be carefully considered in GCL applications (Daniel, 1997).

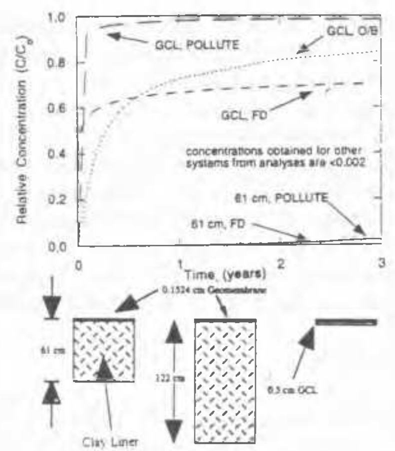
A qualitative comparison of GCL's and CCL's, provided by different authors referring to different criteria is proposed in tab. 2. The performance of a GCL, for most criteria, should be either equivalent to or exceed that of a CCL. However, in terms of liner applications, the considerations of solute breakthrough time, compatibility, and attenuation capacity favours CCL's. Some exceptions can be made for GCL's that use geomembrane supports instead of geotextiles.

An interesting comparison between composite compacted soil barriers of different thicknesses and a typical composite geosynthetic clay barrier has been made (Foose et al., 1996) in fig. 1. Although the GCL gives fully acceptable results, in terms

Table 2. Potential equivalency between geosynthetic clay liners (GCLs) and compacted clay liners (CCLs) (after Shackelford & Nelson, 1996 and Daniel, 1995)

	Criterion	Equivalency of GCL to CCL			
Category	for Evaluation	GCL Probably Superior	GCL Probably Equivalent	GCL Probably Inferior	Site or Product Dependent
Construction Issues	Ease of Placement	X			
	Material Availability	X			
	Puncture Resistance			X	
	Quality Assurance	X			
	Speed of Construction	X			
	Subgrade Condition				X
	Water Requirements	X			
	Weather Constraints				X
Contaminant Transport Issues	*Attenuation Capacity*			X[1]	X
	Gas Permeability				X
	Solute Breakthrough Time	X[2]		X	
Hydraulic Issues	*Compatibility*	X[2]		X	
	Consolidation Water	X			
	Steady Flux of Water		X		
	Water Breakthrough Time				X
Physical/ Mechanical Issues	Bearing Capacity				X
	Erosion				X
	Freeze-Thaw	X			
	Settlement-Total		X		
	Settlement-Differential	X			
	Slope Stability				X
	Wet-Dry	X			

(1) Based only on total exchange capacity, TEC
(2) Only for GCLs with a geomembrane



Illustrations of the Three Liner Systems Modeled.

Input Parameters for Models.

Parameter	Value or Description
Type of Contaminant	inorganic
Depth of Leachate	30 cm
Thickness of Geomembrane	0.1524 cm
Width of Defect	0 4 cm
Length of Defect	91 cm
Frequency of Defects	1 per Ha
Soil-Geomembrane Contact	Perfect (Finite Difference and Ogata-Banks) Good (POLLUTE)
Hydraulic Conductivity of Soil Liner	1×10^{-7} cm/sec
Hydraulic Conductivity of GCL	1×10^{-9} cm/sec
Hydraulic Conductivity of Underlying Soil	1×10^{-7} cm/sec
Effective Diffusion Coefficient of Contaminant in Soil and GCL	4.75×10^{-4} cm^2/yr
Longitudinal and Transverse Dispersivity	0
Retardation Factor	1
Length of Simulation	3 years
Closure Criteria for Finite-Difference Flow Model	1×10^{-3} cm
Boundary Conditions for Contaminant Transport	$c(z \geq 0; t=0) = 0$ $c(z \leq 0; t>0) = 1$ $c(z=\infty; t>0) = 0$ where z is the vertical direction

Figure 1. Breakthrough curves of different types of composite liners (after Foose et al., 1996)

of HC, it is possible to observe that, referring to all the adopted models (POLLUTE; Finite-Difference, FD; Ogata & Banks, 1961, O/B) the relative concentration versus time at the exit boundary is much higher when a GCL is used instead of the different CCLs. This fact should draw attention to the proper use of thin liners in the case of governing diffusive transport.

4. SLURRY CUTOFF WALLS

The three basic backfilling mixtures for SW include: (1) cement-clay (usually bentonites) self-hardening slurries; (2) soil-clay mixtures; and (3) plastic concrete mixtures. The new trends and composition of backfilling mixtures, together with the corresponding literature references, are reported in tab. 3. It is apparent that the main concerns in developing new backfilling mixtures are: their compatibility with the pollutants that must be contained, diffusion phenomena minimisation, and sorption capacity maximisation.

If one looks, in particular, at cement-bentonite self hardening slurries, which are the most common backfilling mixtures used in West Europe, it is worthwhile to mention the studies on the influence on HC of factors such as solid contents, curing time, confining stresses, stress-strain behaviour and chemical composition of the permeants (see Manassero et al., 1995)

A comprehensive experimental study on HC versus time has been carried out by Fratalocchi et al. (1996). The experimental results show that the decrease of hydraulic conductivity with time can be fitted by an exponential equation, as reported in fig. 2a. In the same figure experimental data from different mixtures are plotted with the lines that represent the fitting curve prediction and the range of possible estimation errors. The assessed HC's versus time have been based on HC measurements at 28 days. The parameters α of the best fitting functions have simply been related to the cement to water ratio (fig. 2b). An independent determination of α is recommended (Manassero, 1996) for types of cement and/or bentonite that are different from those used in the research.

Detailed information on physico-chemical interactions between CB mixtures and chemical compounds to be contained by SW can be found in the papers of Ziegler et al. (1993); Gouvenot and Bouchelaghem (1993); Finsterwalder & Spirres (1990); Muller Kirchenbauer et al., (1991), Jessberger (1994), Mitchell (1996), Hermanns-Stengele (1997).

5. SOME ASPECTS OF BARRIER DESIGN, CONSTRUCTION AND LONG TERM PERFORMANCES

The main requirements and/or features of passive barriers are here listed in a proposed order of importance:

- low HC is the fundamental feature of passive barriers;
- durability and high compatibility are the abilities to maintain low HC over the long term and with different permeant liquids;
- after these properties related to HC, the attenuation and immobilisation capacity (i.e. sorption, ion inclusion, precipitation enhancement etc.) can be considered as the second basic feature in order of importance, followed by;
- the low diffusion-dispersion parameter, which can govern transport phenomena only within certain ranges of HC values.

The relative importance of HC and diffusion parameters can be appreciated from the graphs of fig. 3. The range of diffusion coefficients of mineral barriers is shown versus their porosity in fig. 3a; the upper asymptotic trend is, naturally, towards the diffusion coefficient in free water; no higher values are possible. The same range of diffusion variations is reported, in terms of contaminant flux, as a function of the Darcy velocity (which is proportional to HC) in fig. 3b. It is possible to clearly observe that only by reducing HC to below 10^{-9} cm/s, can the diffusion play a significant role in terms of contaminant flux. Over this value the

Table 3. Backfill sealing mixtures of cutoff slurry walls (after Manassero et al., 1995)

Additives and main compounds	Improvements and advantages	References
Sodium metacrilates, alkaline silicato-alluminates and other dispersive chemical additives for CB and plastic concrete mixtures	Decreased hydraulic conductivity, increased resistance against acid compounds	Gandais & Delmas, 1989, De Paoli et al., 1991; Esnault, 1992; Gouvenot & Bouchelagem, 1993; Davidovits, 1993; Gandais et al., 1994; Brauns et al., 1997
Calcium bentonite, attapulgite in soil-bentonite mixtures	Constant or decreased with time hydraulic conductivity when permeated with organics	Ryan, 1987; Meseck & Hollstegge, 1989; Khera & Tirumala, 1992
Filling materials (fly ashes, furnace slags, minerals, other by-products) for CB mixtures	Increased unit weight, decreased void ratio, decreased hydraulic conductivity, decreased diffusion coefficient, increased chemical resistance, decreased unit cost	Carlsson & Marcusson, 1989; Meseck & Hollstegge, 1989; Li et al., 1989; Finsterwalder & Spirres, 1990; Tedd et al., 1993; Brauns et al., 1997; Hermanns-Stengele, 1997; Gouvenot & Raillard, 1997
Microfine cement in CB mixtures	Decreased hydraulic conductivity and diffusion coefficient	De Paoli & Marcellino, 1992
Treatment of clays with ammonium cations for CB and soil-bentonite mixtures. Use of other sorbent materials	Increased sorption capacity	Boyd et al., 1988; Marbach, 1988; Hatfield et al., 1992; Smith & Booker, 1993

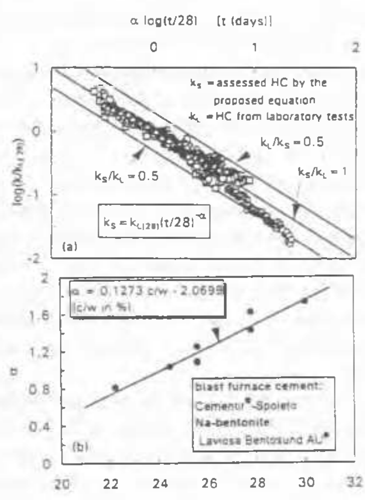


Figure 2. (a) Hydraulic conductivity vs. time of some cement-bentonite mixtures and (b) assessment of exponent α on the basis of the cement content (after Fratalocchi et al., 1996)

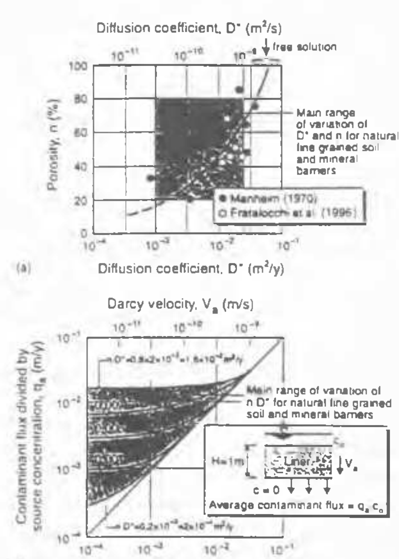


Figure 3. (a) Range of diffusion coefficients for soils and mineral barriers and (b) relative importance of diffusive and advective transport through mineral barriers (adapted from Manheim, 1970; Rowe, 1988; and Jessberger, 1995)

whole contaminant flux is governed by advection, even in the worst case of the highest diffusion coefficient

The importance of the reactive nature of passive barriers, in terms of attenuation capacity associated to compatibility characteristics, is illustrated in the paper by Shackelford (1997) that has been presented during the panel discussion at this conference.

The main geotechnical issues related to the basic requirements of the previously mentioned passive barriers can be considered by referring to the design and construction phases and to the control of the long term behaviour

The design phase is characterised by the choice of materials and components of the barriers followed by suitability testing and transport phenomena simulation. As far as transport phenomena simulation using theoretical models is concerned, many important topics are still under discussion today such as stability and reliability of numerical models and the simplistic nature of analytical and semi-analytical models which, in many cases, do not allow one to take subsoil heterogeneities and complex boundary conditions into account (TC5-Shackelford et al., 1997).

Moreover, the influence of coupled flow phenomena, unsaturated porous media, effective porosity, anion exclusion, matrix diffusion, non-linear and rate dependent sorption, complexation and, biodegradation can play a significant role on the barrier effectiveness even though they are neglected in most of the current modelling approaches (TC5-Shackelford et al., 1997).

Finally, the need of implementation of an "associated" modelling approach in which a local model (e.g. one-dimensional) of the low permeability barrier system would be solved separately and coupled with a full-scale transport code as a source term (Rabideau et al., 1996) should be mentioned.

In the following part of this paper, attention is focused on the choice of appropriate boundary conditions looking in particular at the interpretation of laboratory tests for the assessment of advection dispersion reaction equation (ADRE) input parameters. However the importance of boundary conditions also reflects on the results of modelling the barrier full scale behaviour (Rabideau et al., 1996).

Construction procedures, quality control and final acceptance criteria deal with further important issues within the geotechnical field; looking in particular at the problem of scale effect. The singling out of index properties which play fundamental roles in addressing quality controls and final acceptance criteria is one of the most important goals to be pursued with further research

As far as long term performances are concerned, the durability of different materials and barrier components, the "evolution" of pollutants that must be contained, and controls by monitoring systems are the key issues.

5.1 *Some consideration related to laboratory suitability testing of mineral barriers*

The choice of appropriate boundary conditions often represents a major source of uncertainty in practical applications involving contaminant transport modelling via the advective-dispersive-reactive-equation (ADRE) e.g. the interpretation of laboratory tests or the simulation of field scenarios (TC5-Shackelford et al., 1997).

Fig. 4 shows an example of a possible misleading interpretation of a rather simple decreasing source single reservoir diffusion test (DSSRDT) carried out in the laboratory, when the correct boundary conditions are not recognised. The experimental and theoretical concentration profiles in the reservoir and in the soil sample at the end of the test are shown on the left, considering two different boundary conditions that are represented by the continuous and dashed lines. The concentration trends versus time in the reservoir are reported on the right together with the same concentration profiles on the left along the soil sample at the end of the test.

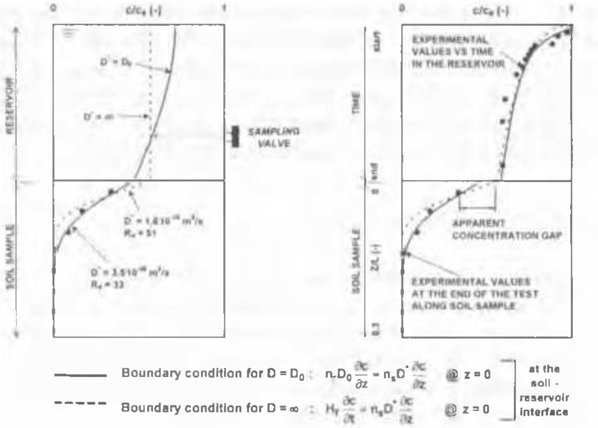


Figure 4. Influence of boundary conditions on the interpretation of decreasing source single reservoir diffusion tests

In this particular case the diffusion coefficient in the free water of the reservoir D_o is higher but still comparable with the effective diffusion coefficient in the soil, D*, therefore the boundary condition between the reservoir and the soil sample cannot be simplified, as shown in the second equation (dashed line), which could be considered reliable only in the case of the ratio D_o /D* going towards infinite values, as generally occurs only in the case of stirred solutions in the reservoir.

On the basis of these considerations it is also possible to obtain a simple and reliable explanation of the experimental concentration gap which often appears across the reservoir-soil boundary in this kind of test. This gap, which was observed by several researchers (Rowe et al., 1995; Dott and Low, 1962; Kemper and van Schaik, 1966; Crooks and Quigley, 1984; Quigley and Rowe, 1986, Manassero et al. 1995), seems to be a function of the position of the reservoir sampling valve, rather than to be related to a localised increase of sorption capacity on the top surface of the soil sample at the boundary with the reservoir, as hypothesized by some of the aforementioned researchers.

The main components of typical laboratory equipment for column tests are sketched on the left of fig. 5. A transformed equivalent layered system is shown on the right of the same figure together with the theoretical relationships that link the parameters of the actual and transformed systems. Reference has been made to conventional one-dimensional differential ADRE. No localised concentration discontinuities have been considered at the connections between the different components of the laboratory equipment, for the sake of simplicity.

The transformation, which results in a equivalent layered column with porosity n=1 and retardation factor R_d=1, has been

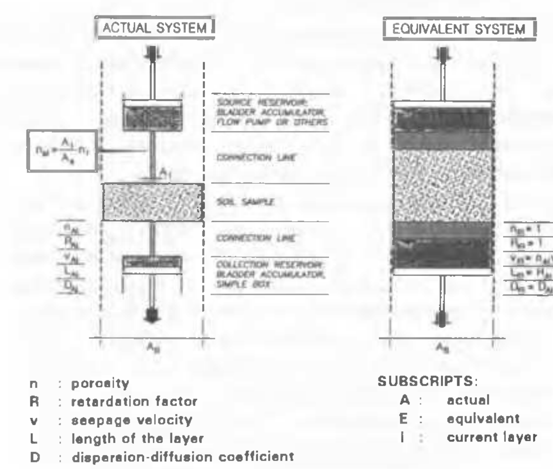


Figure 5. Laboratory column test equipment and equivalent layered profile

proposed in order to be able to evaluate the most appropriate boundary conditions for the interpretation of a laboratory column test, carried out with this kind of equipment,. Under the aforementioned assumptions this transformation is fully consistent, from a theoretical point of view and gives the original concentration distribution with time and along the original column length, by simply considering the geometry scale factor $L_{EI}/L_{AI}=R_{AI} \cdot v_{AI}$. In this way a uniform seepage velocity of the permeant solution along the whole column can be simulated and, therefore, if one imagines it moving at the same seepage velocity of the solution, it is possible to simplify the problem by dealing with a simple diffusion scenario, with moving boundaries between different layers thus temporarily avoiding other considerations on sorption and advection phenomena.

If one then compares the diffusion parameters of the layers that sandwich the soil sample of the transformed column with the expected values of the soil sample diffusion coefficient, it is possible to evaluate the most appropriate from among those boundary conditions listed in tab. 4. Some of these boundary conditions can be imposed by simply using the current closed form solutions of ADRE today available in literature (van Genuchten and Alves, 1982).

For example, in the case of very thin and rather long connecting lines, their transformed diffusion coefficient are usually very low ($D_E \Rightarrow 0$); in this case it is possible to theoretically demonstrate that the trend is towards the 3rd type boundary condition (Shackelford et al., 1997) at the entrance ($v_c - D \cdot \partial c/\partial z = vc_0$) and the second type at the exit ($\partial c/\partial z=0$).

If the transformed column test equipment results in different diffusion parameters and geometries for the different layers but still ranging within the same order of magnitude, a numerical solution that considers mixing zones and/or moving boundaries could be required in order to obtain reliable interpretation of the test results, otherwise different boundary conditions of the available closed from solutions must be used for sensitivity studies in order to investigate the upper and lower bounds of the possible results of the test interpretation.

After choosing the appropriate boundary conditions for the considered column test, it is still important to carry out the appropriate corrections to the output concentrations in order to take into account the apparent retardation, due to the travelling time of the solution within the connecting lines and the dilution effect due to the initial amount of pure water present in the exit piping system and reservoir. The sampling frequency can also have a certain importance, as shown in fig. 6, where the theoretical gaps, in terms of breakthrough curves between two different boundary conditions, and the effects of the equipment geometry are shown for typical transport parameters of a mineral barrier material.

As already mentioned, the assumptions on boundary conditions also play a fundamental role when ADRE is used for modelling the mineral barrier in the field scale (fig. 7). In the case of diffusion and positive advection, it is possible to observe that exit boundary conditions of the second type, at X=L or of the first type, at X=∞, significantly underestimate the pollutant flow with respect to the first type exit boundary condition at X=L which is in fact closer to the actual conditions of most landfill sites.

Table 4. Laboratory column tests and appropriate boundary conditions

ENTRANCE	EXIT
$D_E = \infty \Rightarrow c = c_0$	$D_E = \infty \Rightarrow$ c @ z = L is a function of reservoir geometry and sampling procedure
$D_E = 0 \Rightarrow vc - D \cdot \partial c/\partial z = vc_0$	$D_E = 0 \Rightarrow \partial c/\partial z = 0$ @ z = L
$D_E = D \Rightarrow -\infty<z<+\infty$ $c = c_0$ $-\infty<z<0$ @ t = 0 geometry of source reservoir is important in this case	$D_E = D \Rightarrow c = 0$ @ $z = \infty$ geometry of source reservoir is important in this case
it is important to keep $c = c_0$ in the source reservoir supplying solute and or solution	it is convenient to refer to the effluent solute mass

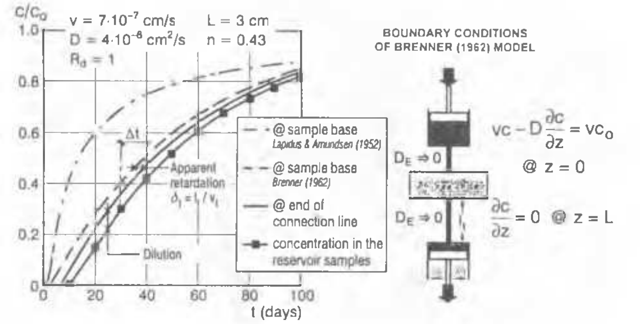


Figure 6. Importance of boundary conditions, apparent retardation and dilution effect on column test interpretation

The opposite can be observed if one looks at the graph on the left, in terms of concentrations. The most reliable results can usually be obtained by referring to numerical solutions that are able to take the mixing zone at the exit boundaries and the finite mass at the entrance boundary into account (Rowe at al., 1995).

5.2 *Modelling the Interface Between Barriers and Surrounding Environment*

The risk analysis for a landfill or polluted site, in terms of aquifer potential pollution, involve the interface between the barrier and the aquifer. Generally speaking barrier systems are designed simply by following prescriptive indications of different regulations, whereas the pollutant impact on the aquifer is evaluated using transport models with simplified boundary conditions, as shown in fig. 8. In this framework the dilution-attenuation-factor (DAF) within a given aquifer has been estimated referring to a constant pollutant recharge with time, which means that an infinite mass of the pollutant is available at constant concentration. In this specific case, it was found that the phenols concentration exceeded the limit concentration by three times at 200m from the landfill, after a certain time, as established by a regional Italian regulation.

A more reliable modelling should take into account: (1): the finite mass of the pollutant in the landfill, (2) the actual release capacity of pollutants in solution, (3) the dilution effect of rain water, (4) the leachate extraction by the leachate collection and removal system and, (5) the sorption capacity of the mineral liner.

Fig. 9a shows the concentration decrease of phenols in the leachate of the considered landfill in terms of the theoretical trend and experimental results. Fig. 9b shows the phenol concentration and flux trends versus time in the aquifer just below the downstream edge of the landfill given by taking the previously mentioned additional factors into account. It is possible to observe that the regulation requirements, in terms of phenols concentrations, are complied just below the downstream edge of the landfill with a factor of safety equal to 2.5. This concentration trend should be used as the input data for modelling the concentration distribution in the aquifer that, in this case, will be

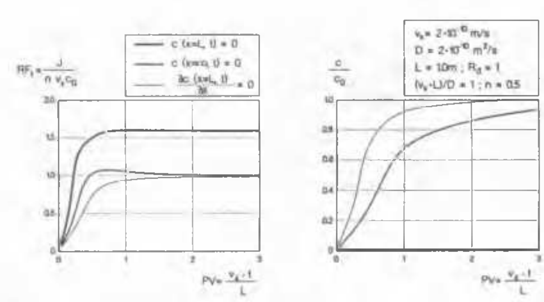


Figure 7. Influence of exit boundary conditions on contaminant concentration and flux

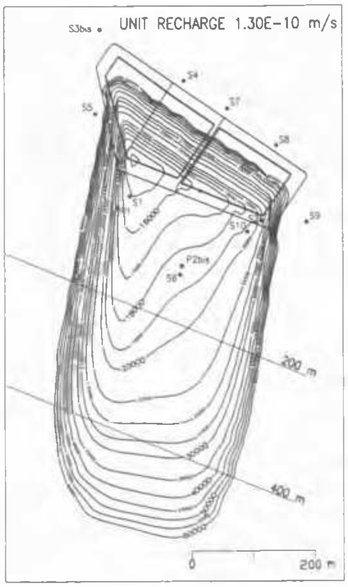


Figure 8. Distribution of Dilution-Attenuation-Factor (DAF) after 90 days obtained with the MT3D model

further reduced by several orders of magnitude at 200m of distance.

5.3 *Key Parameters in Construction Quality Control*

Construction quality control (QC) testing is crucial for the successful performance of compacted soil liners and covers (Daniel, 1990). Construction QC is designed to verify that (1) the materials used in construction are adequate; (2) the construction methods are acceptable; and (3) the liners and covers are adequately protected during and after construction.

As discussed before, there are several key factors which govern the field performances of mineral sealing layers. Some of these, such as diffusion and sorption parameters, can be assessed simply through laboratory tests. These kinds of factors are mainly dependent on the basic features of a soil (e. g. gradation, mineralogy, organic carbon content, etc.) and are generally not influenced by the scale effect as HC is (Daniel, 1990).

A possibility of evaluating the contribution of advective and diffusive-dispersive transport to the contaminant flux and concentration, in the case of poor quality material emplacement is given in fig. 10. It is possible to observe, while also considering the increase of dispersion with seepage velocity ($D_d=\alpha V/n$) within the range of common transport parameters for mineral barriers, that the main contribution to pollutant escaping is due to the advective flow i.e. the HC can be considered as the most important parameter for construction quality control.

It is therefore straightforward to check, with fast classification tests, that the material delivered to the site is the same as that accepted via the laboratory investigation during the suitability phase. Thereafter the main efforts to assure the effectiveness of field barriers should be devoted to the control of large scale HC.

If one, in particular, refers to mineral barriers made of compacted soil layers, which, at the moment, can be considered as the most reliable part of a containment layer of new landfills in the long and very long term, it is possible to define, as in the following, the most important points in order to achieve low HC in the field (Daniel 1990):

1. Using suitable materials.
2. Placing the soil at the correct water content.
3. Properly preparing the surface to receive a lift of soil.
4. Compacting the soil with adequate passing using a proper type of compactor.
5. Protecting each compacted lift from damage.

For more details on tests and procedures for QC of CCL's see Daniel (1993), ETC8 (1993), Daniel & Trautwein (1994), TC5 Report (1997).

5.4 *Long term performances*

The main issues as far as the long term performances of barriers are concerned are: (1) the durability of different materials; (2) the "evolution" of the pollutant to be contained, and (3) the effectiveness of monitoring systems.

As far as the durability of barrier materials is concerned, mineral barriers, in general, and natural clay barriers in particular can be considered the most reliable if compared, for example, with polymeric products.

One possible problem, in the long term, for thick compacted clay liners is that of cracking due to differential settlements of wastes and/or the natural subsoil (Jessberger et al., 1993).

In order to evaluate the long term performances of the barrier systems taking this or other possible problems into account, some authors (e.g. Rabideau et al., 1996) have proposed the use of a degradation factor of the liner in the modelling approach. A problem however arises in the evaluation of this factor versus the several kinds of possible unknown degradation causes in the long term. Effective monitoring systems could help answer this problem in the future.

This paper is not concerned with long term pollutant degradation even though it can play a very important role in some cases, nevertheless, this is another specific field were future research could lead to very useful results for practical applications.

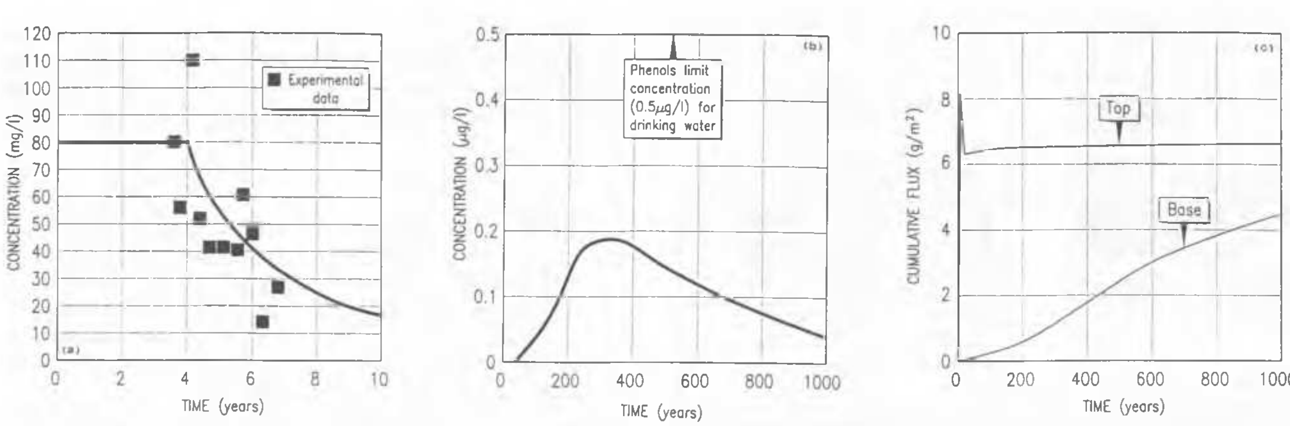


Figure 9. a) Experimental data and simulation model results of phenols concentration in the leachate versus time; b) phenols concentration versus time in the aquifer below the landfill bottom barrier; c) cumulative flux versus time of phenols leaking from the top and the base of the bottom lining system

INPUT DATA

mineral layer reference permeability	:	$K_0 = 10^{-11}$ m/s
mineral layer hydraulic gradient	:	$i = 1.3$ -
mineral layer porosity	:	$n = 0.5$ -
mineral layer thickness	:	$L = 1$ m
mineral layer pure diffusion	:	$D^* = 4.0 \cdot 10^{-10}$ m²/s for $v \le 4.0 \cdot 10^{-8}$ m/s
mineral layer diffusion-dispersion	:	$D = 0.01\ v$ m²/s for $v > 4.0 \cdot 10^{-8}$ m/s
mineral layer seepage velocity	:	$v = ki/n$
aquifer Darcy velocity	:	$V = 4.76 \cdot 10^{-6}$ m/s (plus the contribution from the landfill)
aquifer thickness	:	$h = 3.0$ m
aquifer porosity	:	$n = 0.3$ -
landfill length	:	$l = 100$ m
boundary conditions	:	c = constant @ the top and mixing aquifer @ the bottom

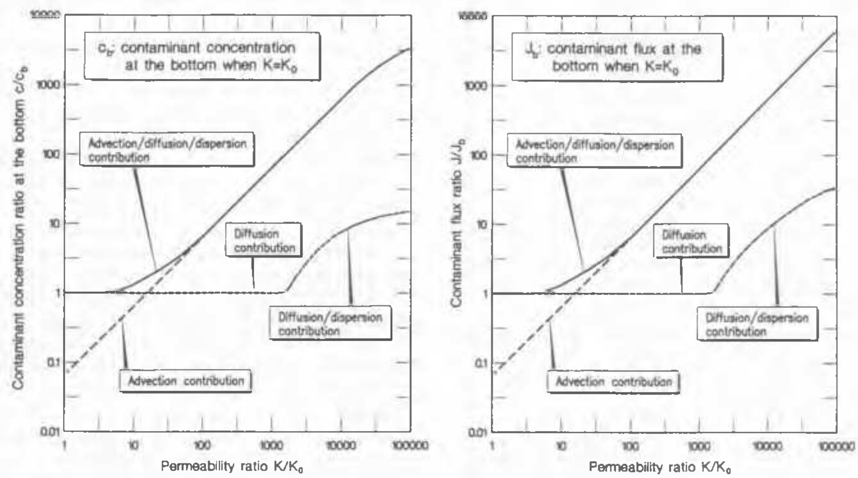


Figure 10. Contribution of advection/diffusion/dispersion to contaminant migration in terms of concentration and flux

6. PRESCRIPTIVE VERSUS PERFORMANCE DESIGN

A rather comprehensive overview of minimum liner systems from the regulations and technical recommendations of different countries is reported in fig.11. In spite of incentives to unite these regulations and recommendations, different approaches are still apparent. This kind of guideline can be defined as prescriptive standards because it gives precise indications on the geometry, materials and profiles of barriers for pollutant control.

Performance standards have however recently been proposed even though they are usually coupled with prescriptive regulations and are therefore not a real alternative. Performance standards or regulations do not define in detail the materials and construction procedures to be used for the barrier system but they require only that certain limit values must be complied with in terms of concentration and or contaminant flux. The compliance with requirements must be demonstrated through the characterisation of transport parameters of liner materials and the modelling of the barrier system and underlying aquifer.

In principle, performance standards would be the better option, at least from an engineering point of view, however the basic problems are these of the reliability of each input parameter for the modelling of the behaviour of the landfill lining performance and the time and space variability of the pollutant targets given by regulations. A tentative list of a group of parameters that should be considered in order to reliably model the barrier behaviour is shown in tab. 5. Apart from the well known parameters related to mineral barriers, a great deal of other parameters such as climate conditions, management and maintenance program, chemical features of the pollutants, etc.. can influence the performance of a barrier.

Performance versus prescriptive standards nevertheless can be considered to be an interesting field of evolution in order to offer a contribution towards improving present regulations and recommendations for a more rational and consistent approach.

7. CONCLUSIONS

When referring to the present State of the Art, the key issues related to the geotechnical aspects of design, construction and long term performance of passive barriers for pollutant containment can be summarized as follows:

- a comprehensive and reliable investigation during the design phase of mineral barriers should include laboratory tests that are able to define basic parameters such as HC, diffusion-dispersion, sorption capacity and compatibility. For this kind of test, topics such as the influence of coupled flow phenomena, effective porosity, saturation degree, anion exclusion, matrix diffusion, non linear and rate dependent sorption, chemical interaction between different compounds, boundary conditions imposed by the different laboratory equipment and related theoretical interpretation approaches still remain a matter of discussion and possible improvement;

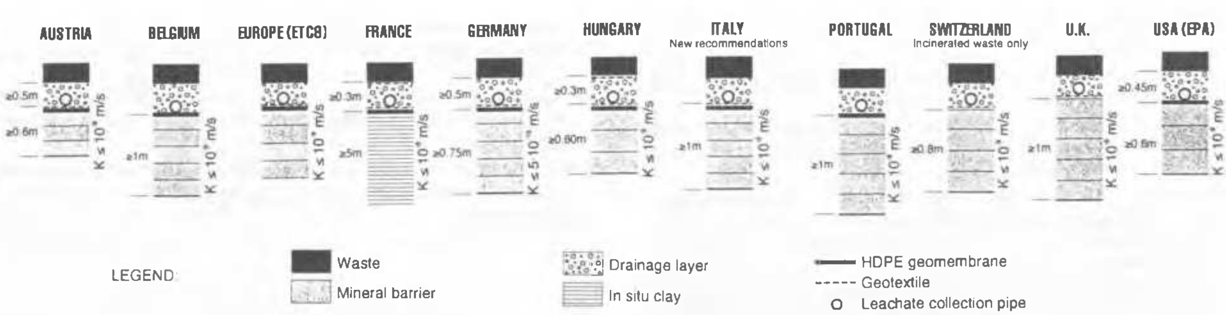


Figure 11. Bottom lining systems for municipal waste landfills from different regulations and recommendations

Table 5. Input parameters for the evolution of confinement barriers effectiveness

SUBJECTS	PARAMETERS
MINERAL BARRIERS	hydraulic conductivity, field capacity, dispersion-diffusion, sorption capacity, mechanical behaviour, compatibility
COLLECTION DRAINAGE LAYERS	hydraulic conductivity, durability (clogging)
GEOMEMBRANES	hydraulic conductivity, diffusion, sorption capacity, durability
WASTE LEACHATE CONTAMINANTS	total mass, density, water content, hydraulic conductivity, field capacity, soluble fraction, actual release, decay, dilution, attenuation
NATURAL SUBSOIL	present hydrogeological conditions and possible future changes, hydraulic conductivity, trasmissivity, storage coefficient, sorption capacity, dispersivity, mechanical behaviour
CLIMATE CONDITIONS	precipitation, evapotranspiration
MANAGEMENT MAINTENANCE AFTERCARE	disposal time history, leachate collection rate history, capping time history
TARGETS OBJECTIVES	limit pollutant concentrations, site vulnerabilities

- during the construction phase, HC becomes the key parameter of the mineral barrier quality control since it is practically the only one that can be significantly influenced by the laboratory to field change of scale. The sensitivity of HC of compacted clay liners and cutoff slurry walls to the quality of the emplacement procedures is well known, as can be seen in the pertinent literature;
- the appropriate boundary conditions and consistency at the interface of the barrier and aquifer theoretical models should be imposed in order to obtain reliable risk analyses and a correct evaluation of barrier effectiveness. Moreover, some authors suggest the use of a degradation factor for the simulation of the long term barrier behaviour. Only reliable monitoring systems could help in the definition of this kind of factor and could also point out any possible unknown aspects of barrier behaviour in the long term;
- performance design (Estrin & Rowe, 1995) tailored to local and specific peculiarities of the considered environment could become the new trend for a modern approach to the landfill design. Within this perspective, further efforts must be made in order to obtain reliable input parameters for modellig the field scale behaviour of the different landfill components.

8. REFERENCES

Bradl H.B., Kliesch K. 1997. Multimineral multilayer clay liners for waste deposits. *Proc. XIV ICSMFE*, Balkema, Rotterdam.

Brauns J., Kast K., Reiersloh D., Schulze B. 1997. Encapsulation of an old industrial waste deposit, geotechnical investigations for a high density cut-off wall. *Proc. XIV ICSMFE*, Balkema, Rotterdam.

Brenner H. 1962. The diffusion model of longitudinal mixing in beds of finite length. Numerical values. *Chemical Engineering Sciences*, 17.

Crooks V.E., Quigley R.M. 1984. Saline leachate migration through clay: a comparative laboratory and field investigation.*Can. Geotech. Jrn.* 21(2).

Daniel D.E. 1990. Summary review of construction quality control for compacted soil liners. *Waste Containment Systems: Construction, Regulation and Performance*. ASCE, New York.

Daniel D.E. 1993. Clay Liners. Chapter 7, *Geotechnical Practice for Waste Disposal*, Chapman & Hall, London.

Daniel D.E. 1995. Pollution prevention in landfills using engineering final covers. *Proc. Green '93*, Balkema, Rotterdam.

Daniel D.E. 1997. Critical issues for waste containment in landfills and contaminated sites. *Proc. XIV ICSMFE*, Balkema, Rotterdam.

Daniel D.E., Trautwein S.J. 1994. *Hydraulic Conductivity and Waste Contaminant Transport in Soil*. ASTM STP n. 1142, Philadelphia.

Dott G.R., Low T.S. 1962. Diffusion of alkali chlorides in clay-water systems. *Soil Sciences*, 93.

Estrin D., Rowe R.K. 1995. Landfill design and the regulatory system. *Proc. Sardinia '95*, CISA, Caglari.

European Technical Committee no. 8 (ETC8) 1993. *Geotechnics of Landfill Design and Remedial Works. Technical Recommendations - GLR*. 2nd Edition. Ernst and Sohn, Berlin.

Foose G.J. Benson C.H., Edil T.B. 1996. Evaluating the effectiveness of landfill liners. *Proc. 2nd ICEG Osaka '96*. Balkema: Rotterdam.

Fratalocchi E., Manassero M., Pasqualini E., Roccato M. 1996. Basic parameters for the design of cement-bentonite slurry cutoff walls. *Proc. The Impact of Industry on Groundwater Resources*, GEAM, Torino.

Gouvenot D., Raillard G. 1997. Utilisation d'un nouveau geomateriau pour confiner un site pollué. *Proc. XIV ICSMFE*, Balkema, Rotterdam

Hermanns-Stengele R. 1997. Waste deposit encapsulation using vertical barriers. *Proc. XIV ICSMFE*, Balkema, Rotterdam.

Jessberger H.L. 1994. Emerging problems and practices in environmental geotechnology. *Proc. XIII ICSMFE*, Oxford & IBH Publishing Co. New Delhi.

Jessberger H.L. 1995. Waste containment with compacted clay liners. *Proc. The Geoenvironment 2000*, ASCE, GSP n. 46, New York.

Jessberger H.L., Demmert S., Heibrock G. 1993. Safety concepts for landfill liners. *Proc. The Environment and Geotechnics*, Paris, LCPC.

Kemper W.D., van Schaik J.C. 1966. Diffusion of salts in clay-water systems. *Soil Sciences*, 30.

Manassero M. 1996. Propagazione degli inquinanti nei mezzi porosi: fenomenologia, inquadramento teorico ed aspetti applicativi in ambito geotecnico. *Atti Il ruolo dei fluidi nei problemi di ingegneria geotecnica.*

Manassero M., Fratalocchi E., Pasqualini E., Spanna C., Verga F. 1995. Containment with vertical cutoff walls. *Proc. Geoenvironment 2000*, ASCE GSP 46, New York.

Manassero M., Van Impe W.F., Bouazza A. 1996. Waste disposal and containment. *Proc. 2nd ICEG Osaka '96*. Balkema: Rotterdam.

Manheim F.T. 1970. The diffusion of ions in unconsolidated sediments. *Earth and Planetary Science Letters*, North Holland Publ. Company, 9.

Mitchell J.K. 1996. Geotechnics of soil-waste material interactions. *Proc. 2nd ICEG Osaka '96*. Balkema: Rotterdam.

Muller-Kirchenbauer H., Rogner J., Friedrich W. 1991. Isolamento delle fonti di inquinamento mediante diaframmi impermeabili e misure idrauliche. *proc. Remediations for polluted subsoils*, Istituto per l'ambiente, Milano.

Ogata A., Banks R. 1961. A solution of the differential equation of longitudinal dispersion in porous media. U.S. Geological Survey. 411-A

Quigley R.M., Rowe R.K. 1986. Leachate migration through clay below a domestic waste landfill, Sarnia, Ontario, Canada: chemical interpretation and modelling philosophies. *Hazardous and Industrial Solid Waste Testing and Disposal*, vol. 6, ASTM-STP 933.

Rabideau A., with contributions from Mercer J. (session co-leader), Andrews C., Chiang C., Grathwohl P., Hayworth J., Culligan-Hensley P., Manassero M., Mott H., Schroeder P., Shackelford C., Teutsch G., van Meurs G., Wilhelm R., Zheng C. 1996. Contaminant transport modeling. *International Containment Technology Workshop*. Baltimora.

Rowe R.K. 1988. Contaminant migration through groundwater: the role of modelling in the design of barriers. *Canadian Geotech. Journal*, 25(4).

Rowe R.K., Quigley R.M., Booker J.R. 1995. Clayey barrier systems for waste disposal facilities. E & FN Spon, London.

Shackelford C.D. 1997. Reactive nature of passive containment barriers. *Proc. XIV ICSMFE*, Balkema, Rotterdam.

Shackelford C.D., Nelson J.D. 1996. Geoenvironmental design considerations for tailings dams. *Proc. Seismic and environmental design of earth dams, concrete dams and tailings dams*. Santiago, Chile.

Technical Committee no. 5 (TC5). 1997. *Environmenta Geotechnics*. Report of ISSMFE-TC5.

van Genuchten M.Th., Alves W.J. 1982. Analytical solutions for the one-dimensional convective-dispersive solute transport equation. *Technical Bulletin n. 1661*, U.S. Dept. Agric. Washington, D.C.

Ziegler C., Pregl O., Lechner P. 1993. Pollutant transport through sealing medium in contaminated land and sanitary landfills. *Proc. Sardinia '95*, CISA, Caglari.