Prof. Peter Brian Attewell

1 - QUALIFICAÇÕES

- Graduação pela Universidade de Birmingham, 1956
- PhD pela Universidade de Sheffield, 1962
- Doutor em Engenharia Civil pela Universidade de Sheffield, 1976
- Membro de "Institution of Civil Engineers"

2 - ACTIVIDADE PROFISSIONAL UNIVERSITÁRIA

- Assistente e Investigador na Universidade de Sheffield
- Professor de Engenharia na Universidade de Durham, sendo responsável pela área de Mecânica Aplicada, Escola de Engenharia e de Ciências Computacionais (1984-94); Director do Curso de Mestado em Geologia de Engenharia (1967-89; 1992-93); e Presidente do Conselho de Estudos de Engenharia (Engenharia Civil, Mecânica e Electrotécnica) em 1988 e 1989
- Professor Visitante da Universidade de Nova Gales do Sul, Austrália, 1990

3 - ACTIVIDADE PROFISSIONAL COMPLEMENTAR

- 1956-59: Actividade no domínio de obras subterrâneas para as firmas MTC e ERCO, e NCB.
- Membro de várias comissões pertencentes a organismos profissionais de engenharia e a instituições universitárias no Reino Unido, Paquistão e Gana
- Director de um Programa ERASMUS da União Europeia, envolvendo as Universidades de Durham, Coimbra, Atenas e Thrace
- Conferências em vários países, Reino Unido, USA, Panamá, Uganda, Tanzânia, Grécia, Hungria, Taiwan, Austrália, França, Índia, Portugal e Irlanda

- Experiência profissional em túneis: Avaliação de deslocamentos à superfície (estabelecimento de metodologias empíricas, trabalhos efectuado para as linhas Green Park e Jubilee do metro de Londres, medições em vários locais de Tyneside Sewerage Scheme e em Langbourgh, Cleveland, livro sobre o tema, e lições mormente num seminário de consultores em Sidney, Austrália); livro sobre 'Tunnelling Contracts and Site Investigation', lições para a indústria sobre 'Tunnelling and Contact Law'.
- Actividade intensa no domínio da consultoria geotécnica, referindo-se, como mais recentes, as seguintes: Norwest Holst-MEPAS (Mersey Estuary Pollution Alleviation Scheme); Norwest Holst Scotland Ltd (problemas contratuais em túneis e em fundações de depósitos); North Tyneside MBC (arbitragem em túneis); Teeside Development Corporation (dragagens); R.T. James, Civil Engineering Consultants (estacas); Entec Engineering (arbitragem em túneis); Exploration Associates Ltd (consultaria geotécnica em geral)

4 - PUBLICAÇÕES

Autor ou co-autor de mais de 100 artigos em revistas científicas, incluindo 6 livros, 2 livros editados, vários capítulos em livros, comunicações técnicas e científicas nos domínios da dinâmica, geofísica, vibrações no terreno, geologia de engenharia, túneis, textura em raios X e cristalografia, teoria da decisão e métodos probabilísticos de análise, estabilidade de taludes, contractos em engenharia civil, e engenharia biomédica. É também autor de numerosos relatórios e de artigos de revisão de livros.

WASTE AND WASTE MANAGEMENT: SOME GEOTECHNICAL CONSIDERATIONS

Resíduos e gestão de resíduos: algumas considerações geotécnicas

PETER BRIAN ATTEWELL*

SYNOPSIS - Waste may be classified into several general types, and there are different systems of disposal. A short consideration of these points is followed by a discussion of the methods of sealed landfill design with reference to some of the preliminary geotechnical factors that need to be taken into account. One example of a sealed landfill in the UK is presented in outline. The implications of leachate and gas generation, together with the choice of liner and landfill capping system and the problems of leakage, are also discussed. Among the conclusions that are drawn, stress is laid on the implementation of construction quality assurance procedures, the need for assessing the potential for groundwater and surface water contamination, and the importance of longer term monitoring for leachate and gas emissions.

RESUMO - Os resíduos podem ser classificados em vários tipos, existindo diferentes sistemas de destino final para esses mesmos resíduos. Nesta apresentação, são feitas algumas considerações elementares acerca destes aspectos, a que se segue uma discussão dos métodos de projecto de aterros confinados, com referência a alguns dos factores geotécnicos preliminares que devem ser tidos em conta. É apresentado um exemplo relativo a um aterro confinado localizado no Reino Unido. São discutidas as implicações da lexiviação e da formação de gás, conjuntamente com a escolha do revestimento e do sistema de cobertura, e ainda, os problemas de fuga de líquidos do aterro. Entre as conclusões que são delineadas, a ênfase é dada à implementação de procedimentos de segurança da qualidade da construção, à necessidade de avaliação do potencial de contaminação das águas subterrâneas e superficiais e à importância de monitorização a longo-prazo para controlo da fuga de líquidos e da emissão de gases.

INTRODUCTORY REMARKS

Ladies and Gentlemen, it is indeed an honour to be invited to give the 1995 Manuel Rocha Memorial Lecture in this great City of Lisbon. The honour is even greater when I see the names of the distinguished lecturers who have preceded me. I give my thanks to the organisers of this lecture, and especially to Professor Rodrigues Carvalho who somehow managed to locate me when I was hidden away in England. Having been Professor of Engineering for many years at one of England's oldest universities, I decided last year that it was time for me to leave academic life and to go back into industry so that I could get involved more extensively in geotechnical design and legal problems as an engineering consultant.

One of the first things that I did when I was appointed so many years ago at Durham University was to attend the First International Congress on Rock Mechanics here in Lisbon

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in 1967. The organiser of that Congress was, of course, Manuel Rocha, and the whole occasion was quite magnificent. The quality of the organisation and the social activities were of a standard that I have rarely experienced at any congress or symposium since that time. And towering above the Congress was Manuel Rocha himself, a giant in the world of civil engineering. It was a compelling experience to visit the LNEC laboratories during that Congress; to see the physical models of dams that were to be constructed, and the methods of stressing them, because at that time numerical methods of analysis had not become a reality. It was only about five years ago when on a trip to the University of Coimbra that I was able to re-visit Lisbon and the LNEC for the first of two occasions, and to have those memories of 1967 come surging back when seeing the laboratories again and the memorial figure of the man to whose name this lecture is dedicated.

1 - INTRODUCTION

At the outset it is necessary to attempt to define the term `waste' because the definition has been of considerable legal interest within the European Community (see Attewell, 1993, footnote 3, pp 6,7). One person's waste may be of economic value to someone else. Even inert demolition waste which is sent to a landfill site could have economic value to another party as, for example, embankment fill. So those who draft legislation need to be very careful indeed with their definitions. In the case of the UK, guidance has been given in the Department of the Environment (DoE) Circular 11/94 which distinguishes between, on the one hand, a substance or object which will not generally be regarded as waste unless discarded as waste by being sold for scrap, consigned for disposal or abandoned, such as:

- worn, but functioning, substances or objects which are still usable (perhaps after repair) for the purpose for which they were made (such as an old car or a machine tool); and
- substances or objects which can be put to immediate use otherwise than by a specialised waste recovery operation (such as by-products formed in the processing of food as a raw material for other food products, power station ash as a raw material for building blocks or as a cement additive);
- substances or objects put to beneficial use by the producer;

and, on the other hand, substances or objects which will generally be regarded as waste even if transferred for value, such as

- degenerated substances or objects which can be put to use only be a specialised waste recovery operation (such as contaminated solvents or scrap metal);
- substances or objects which the holder does not want and which he consigns to a disposal operation, or pays to have taken away, or abandons or dumps, or otherwise deals with as if they were waste; and
- substances or objects put to use by the producer but where the purpose is to relieve him or her of the burden of otherwise disposing of it and the producer would be unlikely to seek a substitute for it if it ceased to be available to him or her.

It may be considered that waste will cease to be "waste" when it is sufficiently recovered as to be usable as a raw material (in the same way as raw materials of non-waste origin) in a process other than a specialised waste recovery operation. At that stage the material will be of such beneficial use as to have eliminated or sufficiently diminished the threat to the environment which was posed when it was "waste".

There are several categories of waste. In the UK the term `controlled waste' covers industrial, commercial and household waste.

Household or domestic waste is from houses, caravans, educational premises, hospitals and nursing homes. It is bio-reactive in the presence of moisture and will be capable of breaking down under aerobic and anaerobic processes, generating heat to stimulate the reaction and creating gases and leachate.

Industrial waste includes any waste from a factory, from premises associated with public transport, postal or telecommunications services or the supply of gas, water, electricity or sewage services. Some of the waste will be bio-reactive like domestic waste, some will be inert and not decompose chemically, and some may be of an organic oily nature and neither breakdown itself nor assist the breakdown of other material with which it might be co-disposed (jointly disposed).

Commercial waste includes waste from trade or business premises, and those used for the purposes of sport, recreation and entertainment. It does not cover agricultural waste, waste from mines or quarries, explosives and most radioactive waste.

In addition there is

Special or hazardous waste which requires a special duty of care in its handling. Special waste is waste that is so toxic or difficult to treat, keep or dispose of that special provision is needed to deal with it. It includes various listed substances, such as mercury and cadmium, as well as inflammable substances and certain medicinal products. It can also include radioactive waste but, in the case of several controlled sites taking this type of waste, higher than expected levels of tritium (levels which have exceeded the World Health Organisation guideline values for gross beta radiation) have recently been found in leachate and water issuing from those sites. A type of `duty of care' already exists for special waste in the UK under its Control of Pollution (Special Waste) Regulations 1980 (as amended). These regulations require a consignment note system to be used by persons producing, transferring or disposing of special waste. Every consignment of waste must be accompanied by several copies of the consignment note, which travels with the waste on the road and is given to the person who ultimately disposes of it. The British Government is currently reviewing the requirements for special waste and is expected to widen the scope of the regulations and to tighten controls.

Special waste, if deposited on its own without suitable confinement, can cause severe damage to the soil in the ground and the groundwater environment.

The expression `Restricted waste' is sometimes used in the UK to describe waste that is intermediate between household and hazardous. `Difficult waste' is the expression for waste which, although acceptable for disposal to landfill in terms of its overall properties, does require a particular method of handling at site beyond the day-to-day procedure.

There is also, of course, `inert waste', consisting of stone and such materials as builders' rubble. By definition it is neither chemically nor microbiologically reactive.

2 - LIABILITY FOR DAMAGE CAUSED BY WASTE

There are obviously legal responsibilities and liabilities for any damage that might be caused by the presence of waste. Anyone who has responsibilities for the disposal and management of wastes within the European Union (EU) does need to be aware of an important proposed Directive. This Directive would impose strict liability on waste disposal operators, and in some cases the producers of waste, for a period of up to 30 years from the occurrence of an incident giving rise to damage or impairment of the environment.

At the time of writing, this Directive is in `cold storage', but what the Commission of the European Communities sees is an integrated package of civil liability to cover problems of historical environmental damage as well as new instances of pollution and land contamination. The underlying contention is that a person should rectify damage that he or she causes; in other words, the polluter should/must pay (if the polluter can be identified, which is not always the case).

Strict civil liability would be applied to cases of damage to the environment caused by activities such as unauthorised waste disposal. Strict liability means that the duty in law is absolute. It does not matter how much care the person or organisation has taken to avoid causing damage. Proof of actual damage is sufficient to make that person or organisation liable under European Community law.

3 - METHODS OF WASTE DISPOSAL

Brief mention is given below of some of the main methods of disposal of waste, including controlled wastes and special (hazardous and 'difficult') wastes. Consideration is not given to wastes such as old cars in scrap yards, but it is necessary to point out that highly contaminated soil, or even rock, that may need to be treated *in situ*, or be removed from a site and treated or deposited elsewhere, in order to allow new development to take place is also special waste.

Household waste re-cycling is one of the best methods of disposal. Materials such as glass bottles and old newspapers are taken to special depositories so that the glass can be made into new bottles and used as aggregate in asphalt, clay pipes, bricks, and for the vitrification for toxic waste, and the paper can become new newspapers. The target in the UK is to re-cycle 25% of household waste by the year 2000 and recover 50% of used packaging by that date. The British Government seeks to stabilise UK waste generation at the 1995 figure of 20 million tonnes per year. Although not household waste there is also an industry for recovering and recycling explosives - 'demilitarising' as it is termed.

Composting means spreading suitable organic and non-toxic waste in a special way so that it will decompose quickly in the presence of water and oxygen and be suitable for using on farmland as a nutrient and fertiliser to stimulate crop production. A considerable proportion of sewage waste is already disposed of to land in this way, but in all cases there is the problem of heavy metals getting into grass, soil and animals, and so entering into the human food chain. Very careful monitoring is needed. The British Government is quite positive about this method.

Anaerobic digestion involves industrial plant for processing household waste to produce high value horticultural growing media. The material that is produced - the so-called 'digestate' - is mixed with other materials to make sure that the product meets the necessary standards for soil improvers and growing media. The UK does not seem to be particularly enthusiastic about this method.

Landfill disposal is one of the common methods of solving the household and industrial waste problem, but it does raise special difficulties. The UK Government is looking for a 10% reduction in the amount of controlled waste going to landfill over the next 10 years. Current quantities of waste to landfill in the UK are about 177 million tonnes, so the reduction must be about 18 million tonnes. Landfill disposal in more special sealed sites will also be needed for hazardous and toxic wastes, and also in some cases for soil that has been contaminated by old industrial processes and which needs to be removed so that new building can take place.

Energy from waste takes the form of incineration which would, on first consideration, seem to be an ideal disposal option for organic waste as a source of fuel for heat and power plants. But it is currently under a European Union political cloud, in part as a result of a US Environmental Protection Agency's draft report on the health effects of dioxins that can enter the atmosphere from incineration. There are also problems with sulphur dioxide and nitrogen oxides, and from particulates and ammonia emissions. Carbon monoxide and hydrogen chloride emissions must also be monitored. Combustion temperatures must be kept greater than 850° Celsius for 2 seconds and oxygen levels greater than 6%. For some incinerators it is required that the combustion gases should be rapidly cooled through the critical temperature range 450° to 200° Celsius in which dioxins and furans can form. It is simply noted that the most toxic dioxin is 2,3,7,8-TCDD, but there are others that are almost as virulent.

There will also be an EU Directive which requires existing municipal incinerators to be upgraded to tighter emission standards, and, if implemented, it would significantly affect most of the UK incineration plants in 1986. Particular environmental objections arise with clinical waste incinerators located in urban environments. It is noted that there are also plants for incinerating military ammunition waste.

As a second reason for incineration, there have been applications in Britain to co-incinerate sewage sludge with domestic waste and with hazardous waste, the organic domestic waste providing all or most of the necessary fluel to support the combustion. Two proposals by Northumbrian Water Plc in the north east of England for this type of incinerator next to existing sewage treatment works were turned down by the Government's Secretary of State for the Environment at about the same time as permission was granted for the construction of a toxic waste incinerator near to the coast and close to a nature conservancy area. Permission was also given for a clinical waste incinerator to be constructed in a built-up area on the south bank of the River Tyne in the north-east of England.

Cement manufacturing kilns are being tested in the UK for the purpose of destroying non-inflammable but combustible waste, including toxic waste. The UK DoE has suggested that the kilns could be used to destroy polychlorinated biphenyls in waste. On the other hand it says that waste should not be sent to kilns where there are "better practical environmental options" - typically where solvent wastes could be re-distilled rather than burned. The question is also raised as to whether these are waste materials in a legal sense, and should therefore be subjected to all the controls that apply to waste, or whether they should be regarded as a fuel because they are combustible. Although there is uncertainty about this method of disposal, and environmental opposition to it, cement manufacturers in the UK have now been given approval by Her Majesty's Inspectorate of Pollution to adopt it. One possible and somewhat unwelcome outcome of this development is that the UK could follow the USA pattern with cement manufacturers, moving into the waste disposal business at a much higher level by burning low calorific value material in competition with established waste incinerating companies.

Transfer of hazardous waste to another country, particularly when that waste is radioactive, is an option that has stimulated considerable opposition from environmentalists. Such opposition has been generated, for example, by a nuclear waste reprocessing plant on the west coast of England which receives spent nuclear material from countries such as Japan. Other hazardous chemical wastes are regularly transhipped between countries. The UK's hazardous waste imports increased significantly in 1994, but there are controls within the European Union because all shipments of such waste must be covered by financial guarantees according to a new 1994 EU requirement. Furthermore, under the United Nations Basle (Basel) Convention, with agreement in 1994, there can be no export of hazardous wastes from OECD countries for recovery in non-OECD countries after the end of the year 1997. Nonetheless, in the UK there has been some industrial pressure to have waste materials destined for recovery operations re-classified as `products' rather than `wastes', and thereby overcoming the ban.

An engineered gas and leachate management system should be designed to accept a range of seepage rates from the very low (the best containment system that can be achieved) to very high (a controlled form of 'dilute and disperse').

There are two main methods of waste disposal as landfill.

Unsealed landfill sites

These are sites where the waste - often uncompacted mixtures of domestic, industrial and sometimes hazardous wastes - has in the past been deposited on the natural ground without any base preparation, underlying seal or any engineered capping seal. Over the years, water has entered the waste, generating gases which have vented to the atmosphere and also producing a 'cocktail' of leachate chemicals which migrate vertically and laterally through the soil and rock underlying the fill, attenuating in concentration, but possibly entering a groundwater system, and so irretrievably damaging an aquifer or passing directly into a controlled water stream or river system. This is the so-called 'dilute and disperse' method of landfill disposal. The assumption usually is that the leachate will have been so diluted over a period of time during its passage through the ground as to present no hazard to groundwater. This system may still be used where it can be clearly demonstrated that there is no hazard to groundwater and surface water supplies. Although the system is not now used extensively in the UK for new landfills, there have been voices arguing that it is to be preferred to a sealed disposal system which considerably slows down the chemical reactions in the waste and so creates a much longer-term hazard. However, UK Government advice in the form of Waste Management documents is quite prescriptive and in line with EU recommendations as far as sealed waste sites are concerned.

Sealed (engineered) landfill sites

These sites are often located in abandoned quarries and exhausted open-pit mines. The base of the site is carefully prepared to the correct gradients in order to allow gravitational flow of leachate to a sump or sumps and a seal is then placed. There are several possibilities for the seal, including such materials as bitumen and concrete, but, as is discussed below, it will most usually consist of up to between about 1 and 1.5 metres of clay, compacted in about 200 millimetre layers to the design density, or it may take the form of a composite seal comprising perhaps a thinner clay mineral layer together with geomembranes, geomembrane protectors and suitable geotextile drainage layers. Leachate drainage pipework needs to be laid and the side slopes to the containment pit often need to be re-graded so that the seals can be held in place during the waste filling process. Some sites may be located in natural valleys, in which case one or even two earth embankments (bunds) must be designed and constructed, generally on the principles applied to road embankment construction and earth embankment dams.

In the case of the UK, recent statistics indicate the following:

- 59% of CLOSED sites were 'dilute and disperse'

- 57% of CLOSED sites were co-disposal
  61% of these were operated on 'dilute and disperse' principles

- 49% of OPERATIONAL sites were `dilute and disperse'
  22% of these were on *in situ* clay
  17% of these were on a single liner
  12% of these have composite liner systems

- 36% of OPERATIONAL sites are co-disposal sites
  54% of these are on the `dilute and disperse' system
  7% only have composite lining systems

- 54% of ALL the sites had no leachate collection system
  18% of ALL the sites relied on recirculation as the main leachate control method
  50% of ALL the sites had no gas control systems

- 70% of the TOTAL WASTE INPUT to the sites goes to non-engineered landfills

The statistics also showed the following in respect of the average remaining lives of UK landfill sites:

- 7 years for the <u>active</u> `dilute and disperse' sites
- 8 years for the *in situ* clay-sealed landfill sites
- 17 years for the single-lined landfills
- 20 years for sites having composite liners

Before discussing some of the principal technical details of waste containment, attention is drawn to some of the general matters that need to be addressed by the designers of the containment facility.

- Acquisition of information concerning national and EU legislation relating to waste disposal and the aftercare of completed sites.
- Anticipation of health and safety issues that are likely to arise both during site operations and after completion.
- Careful consideration of all the risks to site operators and the general public posed by landfill gas.
- Careful assessment of the potential for groundwater and surface water contamination by leachate escape.
- Substantial design analysis of the sealing system and the waste infilling process.
- Implementation of third party (independent of the client and contractor) construction quality assurance (CQA) procedures according to ISO 9000 during site sealing, waste infilling and site capping operations.
- Design and implementation of suitable gas and leachate monitoring systems.

The following technical matters are important.

- There may be insufficient clay soil on the site to achieve the necessary thickness for a monoseal, in which case either clay will have to be transported to the site from elsewhere or, more likely, a liner system involving bentonite may be used. There are two general options with respect to bentonite.

- Powder bentonite to a specified particle size distribution can be mixed (rotovated) with soil in order to produce a layer of between 200mm and 300mm thick that will satisfy the low hydraulic conductivity[1] design requirements. Typically, silty sand can be mixed with bentonite, with the required hydraulic conductivity determining the fractions of the two constituents. Sodium montmorillonite based bentonites have a greater swelling capacity than calcium montmorillonites, such as Fuller's earth, but, because of the possibility of a chemical reversion with the sodium variety, the use of calcium-based bentonite tends to provide a denser and potentially more stable bentonite enhanced soil (BES). Polymer treated compounds can provide greater resistance to leachate action and desiccation.
- Another popular option is to use a geosynthetic clay liner (GCL) consisting of a bentonite layer about 6mm thick between two geotextiles which are joined together by needle punching, by stitching, or by glue mixed with the bentonite. There are four well-known makes of GCL. All are in panel widths of 4 - 6m and length of 25 - 60m, and contain about 5kg/m^2 of Na-bentonite. The sheet joints tend to be overlapped rather than welded since the bentonite in its expanded conditions achieves the seal. With some of the makes, additional bentonite is placed at the joints to assist this sealing process. These makes are:
  - Bentomat®, manufactured by the American Colloid Company in Villa Rica, Georgia, is of needle punched form.
  - Bentofix®, manufactured in Germany and Canada by Nauefasertechnik, is also of needle punched form.
  - Claymax®, manufactured in America by the James Clem Corporation of Fairmont, Georgia, is again of the needle punched form but unlike the two earlier types does not require additional bentonite to be placed at joint overlaps.
  - Gundseal®, manufactured in American by the company Gundle Lining Systems of Spearfish, South Dakota, is unlike the previous three in that there is a bentonite/adhesive mix which is attached to a smooth 0.5mm thick HDPE membrane. Other options are for the HDPE to be textured (roughened to provide extra frictional grip), or for very low density polyethylene (VLDPE) sheeting to be used. At the landfill site, when unrolled, the geomembrane can be at the top or the bottom. The overlaps are of a self-sealing form, but can be welded if required. If the bentonite is at the bottom, then the GCL acts as a composite geomembrane/clay liner. Alternatively the sheets can be laid with the bentonite facing upwards, in which case a conventional geomembrane can be placed on top.
- The seals of a flexible membrane liner (FML) must be formed under very strict third party QA procedures.
- Extreme care must be taken during the transportation of the wide high density polyethylene (HDPE) sheets that are usually adopted for the seal so that they are not damaged. This control will be part of the CQA mechanism.
- Trial welding of the HDPE sheets must be conducted on site in order to give the operatives experience.

[1] The term `hydraulic conductivity' is usually adopted in this paper to describe the facility with which a particular fluid passes through a soil or rock medium. Hydraulic conductivity is a function of the density and viscosity of the fluid and the intrinsic permeability of the medium, the latter depending on grain size, shape and compaction, together with pore space distribution, in a soil and dominently on the discontinuity `architecture' in a rock.

- The sheets need to be carefully searched for damage and holes, and if there are any weak areas they have to be cut out, patched, and re-welded.
- HDPE seam welding must not take place outside strict temperature and wind conditions.
- All welds, preferably double hot wedge with added extrudate, need to be tested under internally-applied air pressure conditions for leaks and if any leaks are found they need to be patched and re-welded.
- HDPE sheeting needs to be laid down the slopes and not across, and will be supported by sandbags fixed to ropes. The sheets will be properly anchored in a trench at the crest of the slope in accordance with the engineering design.
- All landfill sites must have leachate and gas management systems, backed up by routine gas and leachate monitoring particularly at the site perimeter.

Cellular form of landfill site

In the normal cellular form of construction the landfill site is segmented into smaller units, each unit bounded by a so-called `bund' constructed as a clay barrier having very steep sides in order to reduce the amount of clay that is needed and also the lost space for the fill. These bunds may need geotextile reinforcement and they are raised gradually with the fill so that the fill provides lateral support. Figures 1 and 2 show this form of construction in a diagrammatic manner. The cells generally range in thickness up to about 5m and within each cell the waste is covered with a 150mm-300mm thick layer of soil at the end of each working day in order to minimise the dispersion of debris and to reduce the ingress of water. In the USA several foams are available as soil substitutes for this daily cover.

There is also a simple method of performing a preliminary calculation, based for example on the information given in Table 1, of the number of cells that are needed, given data on the amount and type of waste, its degree of compaction, its absorptive capacity, and the amount of rainfall. The moisture content of fresh refuse ranges from 15% to 45% and is typically about 20% on a wet weight basis.

From Table 1 the figure of 11 500 tonnes/year is equivalent to 11 500m^3/year. Assume that the density of waste is very approximately equivalent to that of water, and that the average annual rainfall is 1000mm. Then, based on these assumptions the maximum cell area is equal to the ratio of the estimated annual total absorptive capacity and the average annual rainfall, which is 11 500m^2. Suppose that the area of the disposal site is 100 000m^2. The operational number of cells will then be equal to the ratio of the site area (100 000m^2) and the cell area (11 500m^2), which is 8.7, or 9 in practice, if leachate production is to be minimised. Each cell needs to be sealed at the top when full of waste in order to inhibit further infiltration. In practice a minimum cell area is likely to be about 0.25 hectare (2500m^2) and a minimum cell life of 6 to 12 months will be necessary for efficient operational purposes.

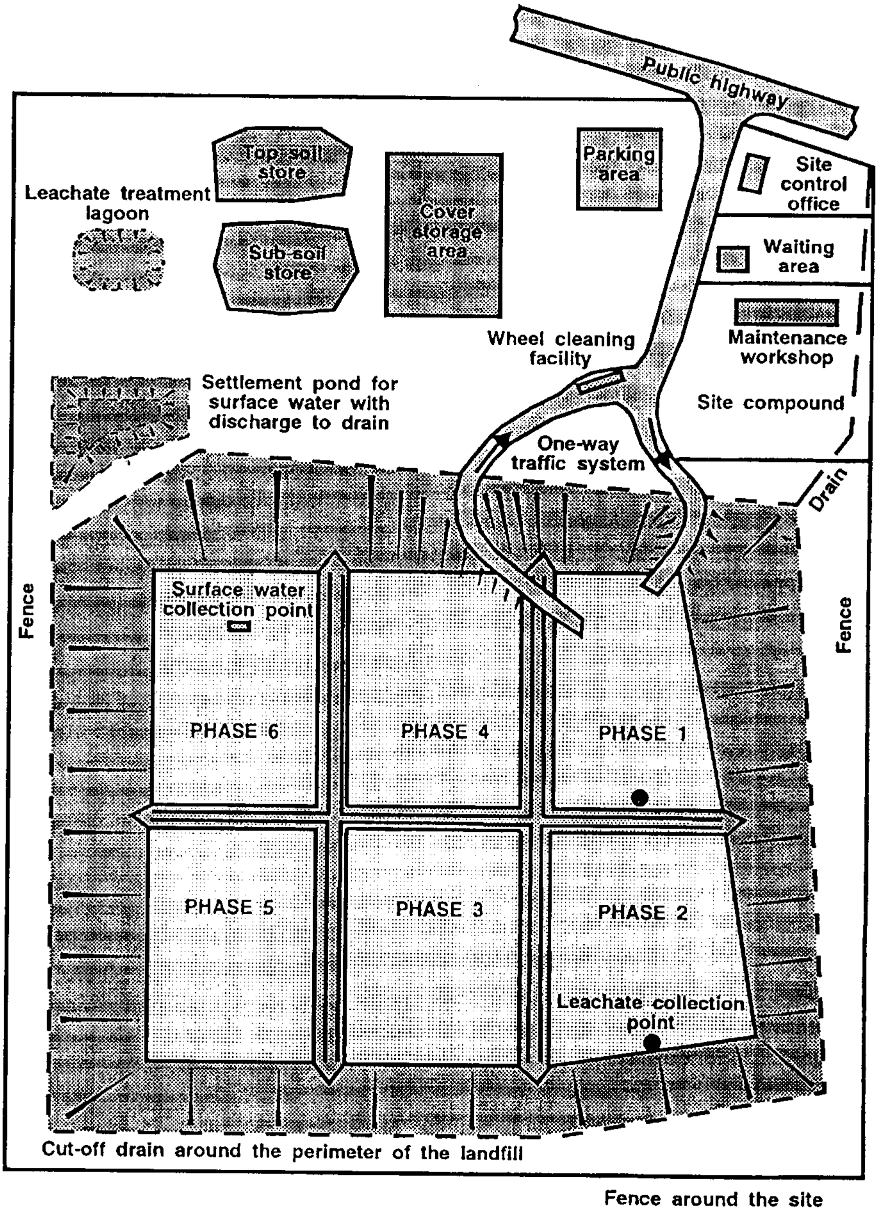


Figure 1 - Diagrammatic indication of waste disposal into cells formed by clay bunds (after Department of the Environment, 1986)

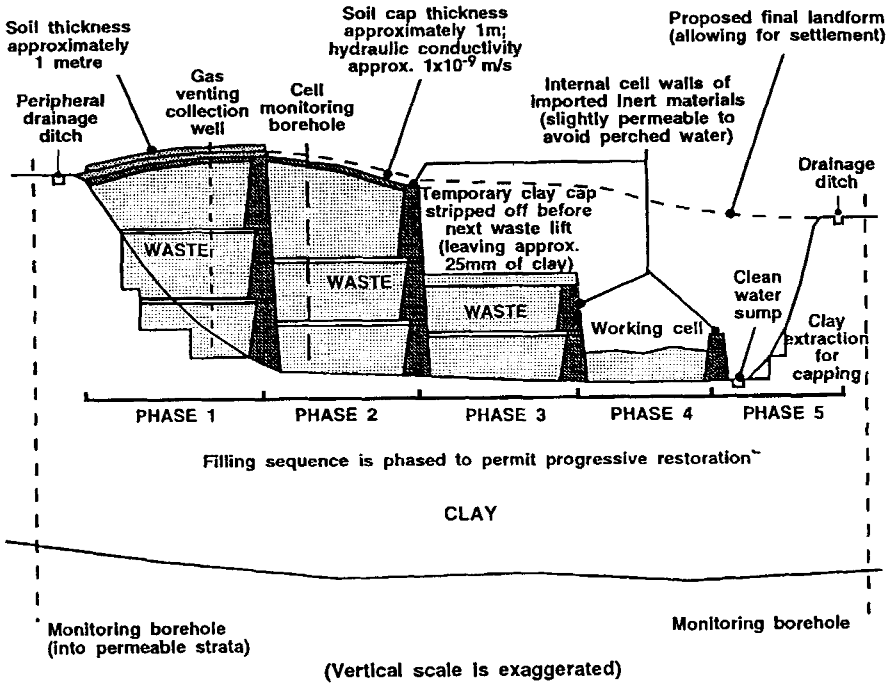


Figure 2 - Diagrammatic cross section of landfilling by cells
(after Department of the Environment, 1986)

Table 1

Example information for the calculation of the number of waste disposal cells

TYPE OF WASTE	EXPECTED DISPOSAL (tonnes equivalent per year)	ASORPTIVE CAPACITY (%)	TOTAL WATER ABSORPTION (tonnes equivalent per year)
Domestic	50 000	15	7 500
Industrial/commercial	30 000	10	3 000
Inert (builders' waste/stones)	20 000	5	1 000
		TOTAL	11 500

Gas venting pipes will be built into each cell as the fill is raised and there will be leachate drainage pipes installed to suitable gradients within in each cell and between cells so that the leachate generated by the biochemical and microbiological reactions which take place over time in the cells will be conducted to a lowest-point sump or sumps. The leachate will then

- either be pumped up into a tanker and removed to another containment site;
- or it may be pumped to a lagoon for aeration, dilution, and then discharge into a main drainage system if available and the owner's permission is granted, or be allowed to drain into a water course if approved by the appropriate statutory agency; alternatively the diluted leachate may be `tankered off' to be disposed of in forestry areas by spraying provided that permission is given by the appropriate regulatory body; or it may be treated by a system of reverse osmosis;

- or it will be re-circulated back into the fill, as a spray, in order to accelerate the breakdown processes in the fill.

Sometimes for large sites the landfill gas, mainly methane, can be removed under slight negative pressures and then burnt for power generation. About 10% of global emissions of methane, which is the most important green house gas after carbon dioxide, comes from landfills.

When all the cells are full, there needs to be a properly designed capping system which can include polymer sheeting but which will incorporate suitable top soil so that vegetation will grow. There is further discussion on this matter below.

Notwithstanding what has been indicated earlier concerning the fact that many old landfill sites in the UK, and some new ones, have no lining system at all, and operate on the `dilute and disperse' principle, all new sites should be fully engineered with a highly impermeable lining of clay, HDPE, or composite clay and HDPE with appropriate geomembrane protectors and drainage layers. Clay seal hydraulic conductivity must be less than or equal to 10^{-9}m/s. For this to be achieved without bentonite supplementation the following geotechnical properties can be used as guidelines:

- percentage fines: greater than or equal to 20-30%
- plasticity index: greater than or equal to 7 - 10%
- percentage gravel: less than or equal to 30%
- maximum particle size: 25-50mm

The hydraulic conductivity for HDPE will usually be taken as 10^{-14}m/s, although some authorities use the figure of 10^{-11}m/s. The latter figure is probably more appropriate after placement and under operational conditions.

5 - CO-DISPOSAL AND LANDFILLS AS BIO-REACTORS

In the UK there seem to be two lines of thinking in terms of the waste itself and the means whereby the breakdown process can be optimised. First, there is the question of co-disposal and then there is the concept of landfill as a big bio-reactor.

Co-disposal

The UK has been the only Member State in the EU pressing to be allowed to continue disposing of household, selected industrial and hazardous wastes together in the same fill. This is referred to as `co-disposal', while the EU refers to it as `joint disposal'. There are, however, certain hazardous substances - the so-called List I and List II substances as defined by the EC Groundwater Directive 80/68/EEC - that cannot be co-disposed with household and industrial waste in sealed landfills.

The UK maintains that co-disposal is the `best practical environmental option' (BPEO) for some industrial wastes. About 2.5 million tonnes of what can be termed `difficult' waste is disposed of in this way to 300 licensed co-disposal sites in England and Wales each year. Notwithstanding what has been stated above concerning List I and List II substances, there has even been a suggestion that low level nuclear waste could be `diverted' to conventional landfills instead of being housed in special repositories. The UK has always been fighting a losing battle with the EU on this matter of co-disposal but, in addition, the whole concept of landfill as a biological reactor seems also to be under attack.

Bio-reactor concept

There have been two fairly recent British Government documents on the subject of non-inert waste infill as a bio-reactor. One of the documents outlines the 'bio-reactor' concept, which involves the pumping in of liquids to the fill in order to stimulate the chemical reactions and thereby the breakdown of the waste. The second paper accepts that there can never be total containment of the products of reaction. All liners leak, and this leakage will be progressive with time. More importantly it says that contained co-disposed fills should be actively designed, operated and controlled as flushing bio-reactors in which the passage of moisture is engineered rather than regarding the contained fill simply as a long-term repository. The idea is to stabilise the waste within a period of about 30 years, and this can perhaps be best achieved by abandoning the system of disposal cells. An important feature of the bio-reactor design is high rate recirculation of leachate in order to encourage methanogenic degradation and thence rapid stabilisation of the fill. Solvents will not to be allowed to be co-disposed in this way and a new bio-assay test is proposed for UK Red List (somewhat equivalent to the EU Directive List 1) substances, which are the most toxic substances, in order to assess their potential for co-disposal. Also, oily wastes tend to be very persistent (which means that they do not break down at all easily) in landfills and so should not be co-disposed of in this manner. They contribute very little to the final moisture content of the landfill and they do not seem to influence leachate generation and hydraulic retention times.

What the UK DoE seems to be saying by way of justifying its position with respect to co-disposal is as follows.

- Do not continue actively to exclude water from the landfill because a dry site is an unreactive site and it will take decades, perhaps centuries, for the waste to become safe.
- High rates of leachate re-circulation within the fill are needed in order to promote breakdown. But this can cause problems because leachate transmission pipes become blocked. Also at the present time in the UK the maximum permissible head of standing leachate in the fill is 1 metre. There is therefore less driving pressure across the landfill lining. Because of the need for a wet site it is now being argued that this leachate head should be allowed to increase so that more of the fill is encouraged to react. But it is also accepted that removal of ammonia could be a problem with greater leachate recirculation.

The UK DoE is also maintaining that landfill caps should be more durable so as to minimise any environmental impact even if a liner fails. But, as is indicated above, while all these ideas are being developed about co-disposal within a landfill which is subjected to an engineered bio-reaction, it does seem that the EU ban on co-disposal will take place and the UK will have to comply unless it can manage to invoke the principle of subsidiarity on this issue within the Community.

It is relevant to note the use of genetically modified organisms, or, as is termed in the UK, 'bugs' for cleaning up contamination and eating waste. In theory, the idea of releasing organisms to render hazardous substances inert is a very attractive one, but currently it is not a fully proven technique. The bugs need to be controlled in terms of where they go and how they multiply, and so there must be a strict regulatory regime in place. The subject of old cars in scrap yards is mentioned above. The bodies of the old East German Trabant cars are made from resin and gun cotton, and because there are so many of these old cars now lying in scrap yards after their owners have moved up to BMWs, it has been suggested that the car bodies could best be broken down by using bugs to gobble them up!

Geotechnical engineers and engineering geologists are familiar with the basics of site investigation - the geological and geotechnical desk study, the observational walk over the site, the putting down of boreholes for ground identification, ground and water sampling and any *in situ* testing, and the laboratory testing procedures in order to acquire data for calculations and design. There are several useful publications on the investigation processes that are important for landfill sites, including: `Geotechnics of Landfills and Contaminated Land: Technical Recommendations "GLC" edited by the German Geotechnical Society for the International Society of Soil Mechanics and Foundation Engineering and published in 1991 by Ernst and Sohn, and `Geotechnics and Landfills and Contaminated Land', which is a technical Guidance Manual prepared by the European Technical Committee 8 and which is based on the German document.

There is also a recent UK draft document which incorporates the Country's official thinking on this subject but which may be subject to substantial change in the final version: `Landfill Design, Construction and Operational Practice', Waste Management Paper 26B, A Draft for Consultation by the UK Department of the Environment, February 1995.

A further UK Government document is `Landfill Co-disposal', Waste Management Paper 26F, A Draft for Consultation by the UK Department of the Environment, February 1995.

A reference for hazardous waste is `Croner's Hazardous Waste Disposal Guide' (1988) Croner Publications Ltd, Croner House, 173 Kingston Road, New Malden, Surrey KT3 3SS, England, 368pp. (ISBN 0954-2922).

The following site investigation features are particularly relevant to the problem of waste disposal.

Geology from the desk study and borehole evidence

Soil

- Determine the depth to bedrock profile over the site.
- Establish the nature of the soil layers, particularly their mineralogy (by X-ray analyses), and their suitability, particularly plasticity, hydraulic conductivity and compactability, as a basal and capping seal, including the resistance to erosion of any fine particle fraction.
- Check if there are any background soil gas concentrations.
- Assess available volumes and thence decide a maximum available thickness for the containment site and the possible need for a composite seal.
- Propose appropriate earth moving, earth storage, and earth placement schemes of work.
- Consider slope angles and thereby the necessary shear strength parameters for stability; maximum slope angles (batters) are approximately 1 in 3 but if bentonite is used in free form and the bentonite hydrates, then a critical friction angle will be as low as 1 in 7.

Rock

- Establish the rock types, mineralogical composition and stratigraphy beneath and in the vicinity of the landfill.
- Determine whether there is a karstification risk.
- Establish the presence of any faulting which could move over a time period of decades, and particularly in the presence of seismic activity.

- Determine the discontinuity structure in the underlying rock strata (systematic jointing and random joints; discontinuity separations and infillings).
- Design suitable *in situ* permeability tests for water and for gas, remembering that gas is more `searching' than liquid. The Darcy flow rate of landfill gases is inversely proportional to viscosity, and because landfill gas has a lower viscosity than that of leachate its flow rate will be higher for the same driving pressure. There may also be gas seepage through diffusion.

Hydrological

- Estimate current groundwater levels in the area and the hydraulic gradients, adopting groundwater tracing tests and trial pumping tests. Piezometers at the perimeter of the site installed for the pumping tests can be used for long-term monitoring.
- Assess the effects of short-term lowering of the groundwater table.
- Be aware of any groundwater protection zones and attempt to model computationally groundwater (and potential contaminant) movements towards aquifers, streams, rivers and any other controlled waters. There are software houses such as, for example, Oxford Geotechnica International (Thomas et al., 1994; Welch, 1995 a, b; Thomas and Welch, 1995) offering this facility.
- Establish the location of any aquifers that could be affected by leakage from the landfill, and of any springs in the vicinity of the landfill area. This is an absolutely essential prerequisite.
- Investigate the presence and nature of any current groundwater abstractions in the vicinity of the site.
- Determine groundwater chemistry as a baseline prior to landfilling. The use of abstraction pumping requires care in order to avoid imposing contamination.
- Acquire information on precipitation, evaporation and groundwater recharge in the area.

Additional information

- Analyse the stability of existing slopes.
- Check for the possibility of subsidence caused by any old mineworkings and groundwater abstractions.
- Identify any structures that could be affected by the ground and groundwater changes.
- Establish the possibility and degree of any seismic risk.

There are obviously further factors to be considered, such as those relating to legal issues, planning, including wayleaves and access to the site, and sociological factors, including the effects of wind, dust, odours and noise on adjacent populations.

7 - DESIGN OF A SEAL

Basal seal

There is a substantial volume of easily-accessible literature devoted to the subject of sealed landfill design. Some elements of the design are outlined below, beginning at the base and proceeding through the liner to the waste infill.

- Compressible soil, stones and protrusions need to be removed from the site, any top soil being placed around the perimeter to act as a noise baffle and to be available for placement at the top of the cap when the infilling is completed.
- There will be a sub-grade layer, 300mm-500mm thick, usually of sand or gravel at the base of the seal and this serves as the drainage layer. As a guide, and following a USA EPA requirement, the drainage layers should have a hydraulic conductivity of at least 10^{-2} m/s.
- In a few cases, about 50% in the UK, there will clay soil of sufficiently low hydraulic conductivity on the site for the construction of a basal sealing layer, usually between 1 and 2 metres thickness. This will be done in layers of about 200 millimetres using several passes of a sheep's foot (preferred) or vibratory roller. The minimum compaction weight, foot length and number of passes will be about 18 000kg, 180-200mm, and 5, respectively. In the USA the Environmental Protection Agency (EPA) requires the compacted soil layer to be at least 0.9m thick for the containment of hazardous waste and for the maximum permeability to be 10^{-9}m/s. In the case of non-hazardous waste the minimum thickness of a compacted clay soil liner should be 0.6m.

  Clay soil placement lifts can be either horizontal or parallel to side slopes, The latter is not the preferred option for side slopes steeper than 1 (vertical) to 2.5-3 (horizontal), but in general lifts parallel to the side slopes are preferred because the effect of a zone of `poor' material, or imperfect bonding of lifts, is less with parallel lifts (Daniel, 1993).

  Several laboratory tests on the clay soil, as indicated in Table 2, would normally be specified.

In particular, the requirement for a clay seal hydraulic conductivity to be not greater than 10^{-9}m/s may be checked in two ways:

- First, indirectly, by conducting laboratory compaction tests and falling head hydraulic conductivity tests on the material and plotting the relations between the two. Then, *in situ* density tests can be performed on trial compactions before the actual construction and the *in situ* hydraulic conductivities derived indirectly from these density values. This is not an ideal method but it is convenient and cost effective.
- Directly by means of *in situ* hydraulic conductivity tests because of the unreliability of results from laboratory tests on small samples when translated into the larger *in situ* mass. These tests, typically between 10 and 20, may often be performed in a single cased borehole using either a constant or falling head. The *in situ* hydraulic conductivity using natural, on-site clay may well be as low as 10^{-7}m/s and so some assistance may be needed, as noted below, in order to reduce the value to at least 10^{-9}m/s.

Minimum hydraulic conductivity of a clay soil tends to occur with the moisture content on the wet side of optimum for maximum dry density in a standard compaction test. With this over-saturation the fines that are present are given a chance to expand and so decrease the hydraulic conductivity. As a general guide, test results suggest that minimum hydraulic conductivity will be at optimum moisture content plus about 2% to 4%. The results in Figure 3 for a landfill site in England indicate that $k_{minimum}$ is at $W_{optimum}$ plus 4% for that particular clay soil.

Table 2

Laboratory tests to be specified on clay liner material in order to assess its suitability for use as an engineered low permeability seal

TEST	PARAMETERS	PROPERTY	USE IN DESIGN
Atterberg limits	PL, LL, PI	Physical behaviour	*Material suitability and placement design
Particle size distribution (wet sieve, hydrometer pipette)	Percentage clay, silt, sand, gravel	Material composition and variability	*Material suitability
Specific gravity	G_s	-	*Calculation of percentage air voids
4.5kg or 2.5kg compaction test to reflect compaction to be used in construction	Compaction curve: optimum moisture content and maximum dry density	Remoulded behaviour	*Material suitability for engineering behaviour *Quality assurance
Unconsolidated undrained triaxial tests	c_u	Short-term shear strength behaviour	*Material suitability *Short-term slope design and stability modelling *Bearing capacity
Consolidated undrained triaxial tests with pore pressure measurement	c' and ϕ'	Long-term shear strength behaviour	*Material suitability *Long-term slope design and stability modelling
Permeability: constant head, falling head etc. (constant head test in triaxial cell will often be written into the guidelines)	k coefficient	Remoulded permeability behaviour	*Material suitability *Engineering specification *Quality assurance *Rate of leachate migration
Moisture content	w	Natural moisture content percentage	*Material preparation *Material suitability *Engineering specification
Slake durability	-	Potential weathering	*Material suitability *Material preparation
Oedometer	Coefficient of volume compressibility m_v and consolidation settlement s_c	Reduction in liner thickness with surcharge loading	*Consolidation properties

Because in most cases there will be insufficient clay soil having suitable properties available at the site as a monolayer sealant, a composite lining will be needed. There are different materials and methods of construction using clay mineral sealing layers, geomembranes, geotextiles, and sometimes mineral layer supplements such as the Bentomat®, Bentofix®, Claymax® or Gundseal® blankets mentioned above. For the containment of monofill hazardous waste and co-disposed waste containing hazardous chemicals a composite liner containing mineral layers, at least one HDPE geomembrane and perhaps two membranes with protectors, and ideally a Bentomat® or equivalent layer, all interspersed with suitable geotextile layers would be recommended as the very expensive but necessary way forward.

A composite liner has recently been constructed for a household waste site near the city of Perth in Scotland. This is a valley site which has required the construction of a rockfill embankment (bund) on sound bedrock at one end for the retention of the infill. Within and outside the landfill the side slopes are 1 in 3 and 1 in 2, respectively, and the rockfill was placed according to Table 6/4, Method 5 of the UK Department of Transport Specification for Highway Works. Because there is spring water emanating from the valley sides two schemes of sealing protection were designed: one for the valley bottom and one for the sides.

Figure 4 shows in cross-section the original conceptual design for the seal at the valley bottom, indicating the geotextile protectors at the top and bottom with the high density polyethylene sheeting at staged distances in between.

The general sequence of seal construction from the top down was envisaged as follows:

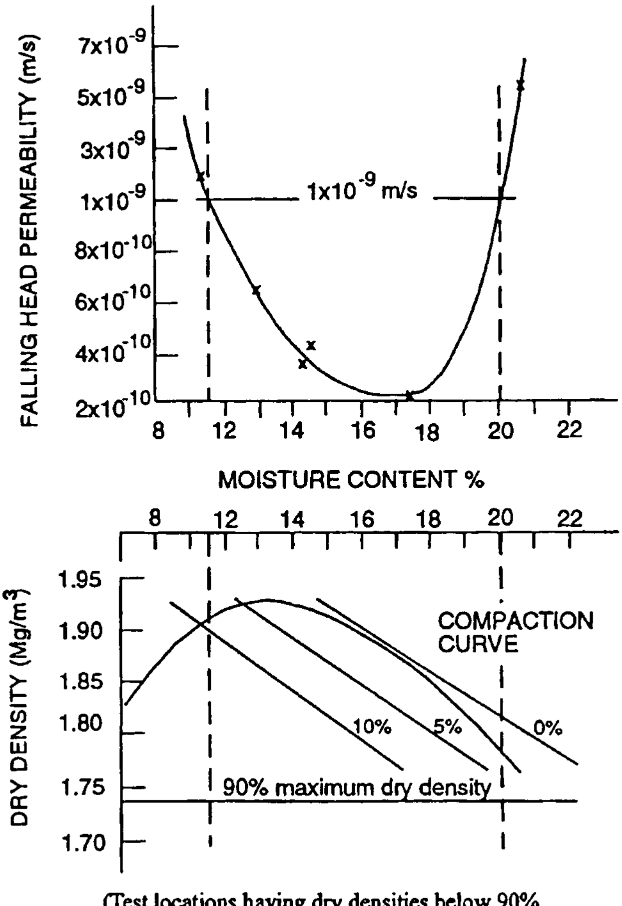
Polypropylene geotextile, 1200g/m^2 (to protect the HDPE primary lining)
HDPE primary lining, 2mm thick, roughened on the underside
HDPE Gundseal® 0.75mm thick, roughened on the underside
Clay mineral layer, bentonite-enriched soil, 600mm thick
HDPE lining, 2mm thick
500g/m2 geotextile protector geofabric
300mm thick or thereabouts crushed rock blanket
to intercept valley seepages and
to conduit water to drainage pipes in the valley bottom below the infill

Figure 5 shows the somewhat simpler conceptual configuration of sealing up the valley sides.

The actual construction design changed somewhat from the conceptual design, the base of the valley comprising the following sequence from the top down:

32-75mm crushed rock, 825mm maximum thickness at the lowest point
10-32mm crushed rock, 300mm thickness
350g/m^2 geotextile
Sand layer, 100mm thickness
HDPE 2mm thick roughened on the underside
Gundseal® geosynthetic clay liner (GCL) having approximately 5kg/m^2 Nabentonite and combined with a 0.75mm thick HDPE sheet placed on the clay blanket
Clay mineral layer, 600mm minimum thickness tapering to zero when 3m higher than the floor of the channel at the contact with the valley side seal, and having a hydraulic conductivity less than or equal to $1x10^{-9}$m/s conductivity less than or equal to $1x10^{-9}$ m/s conductivity less than or equal to $1xl0^{-9}$m/s
500g/m^2 geotextile protector geofabric
10-32mm crushed rock, 300mm thickness having an overlying nominal 0-10mm depth of dust, for sub-liner drainage
32-75mm crushed rock, 300mm thickness, for sub-liner drainage

The porous pipes for leachate drainage at the bottom, as shown in the conceptual design, were changed at the final construction stage when there was concern as to whether they could give long-term support to a 9 metres high bund and 30 metres height of waste infill. Instead, what was actually used was a trench containing a 300mm diameter HDPE slotted pipe having a pea gravel and separator surround. There is the same type of slotted pipe system for drainage on both sides of the valley, with all three pipes outfalling into the leachate lagoon system. These pipes also serve for leak detection and are monitored on a regular basis. The geotextiles, supplied by Geofabrics of West Yorkshire, England, were constructed from virgin staple fibres of polypropylene. Joints were overlapped by 400mm and sealed by hot welding.



(Test locations having dry densities below 90% maximum dry density line are subjected to further compaction)

Figure 3 - Dry density, moisture content and permeability relations for a clay soil at a landfill site in England

Landfill sealing systems such as these are expensive to install, but it must be remembered that they have to be operationally effective for several decades and the cost calculations performed on that basis. Figure 6 shows a generalised sequence of base sealing that has been used elsewhere, and this comprises a single HDPE layer with a mineral sealing layer but with four geotextile layers and a leachate drainage layer.

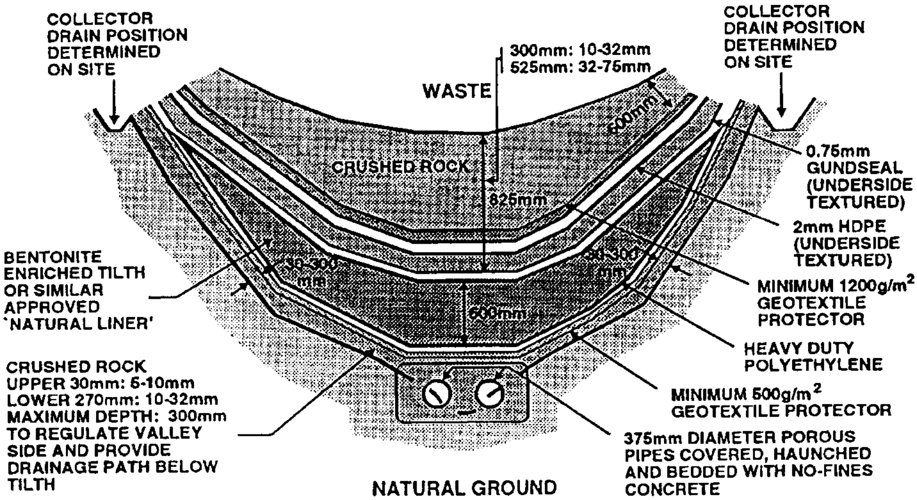
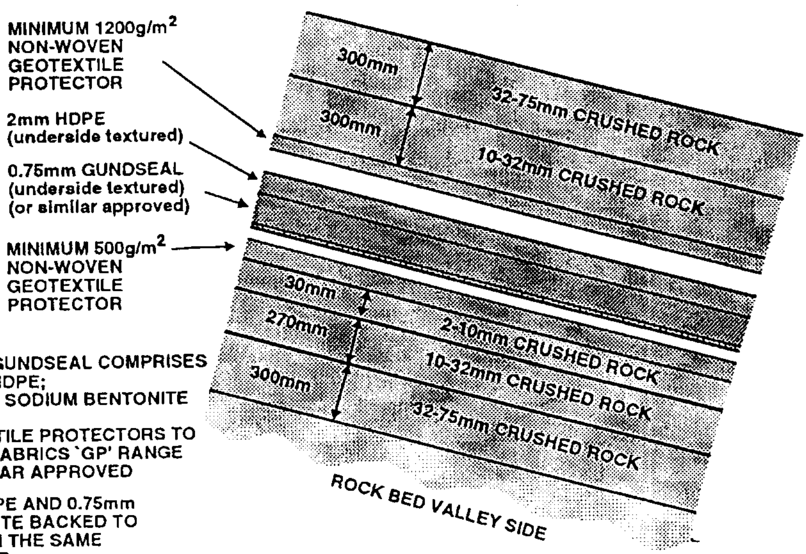


Figure 4 - Binn landfill site, Glenfarg, Perth, Scotland.
Conceptual design. Section at the valley bottom.



NOTES:

1) 0.75mm GUNDSEAL COMPRISES 0.75mm HDPE; 4800g/m² SODIUM BENTONITE

2) GEOTEXTILE PROTECTORS TO BE GEOFABRICS 'GP' RANGE OR SIMILAR APPROVED

3) 2mm HDPE AND 0.75mm BENTONITE BACKED TO BE FROM THE SAME SUPPLIER

Figure 5 - Binn landfill site, Glenfarg, Perth, Scotland.
Conceptual design. Section at the valley side.

Capping seal

When waste infilling has been completed it is then necessary to `cap' the site with (relatively) impervious cover in order to seal in the waste and to prevent the access of atmospheric water. Although a (clay) mineral capping seal, with top soil above, is acceptable, a composite seal is the normal solution. Geomembranes for capping can usually be thinner (say, 1mm thickness) and geomembrane protectors lighter (say, 500g/m^2) than in the case of basal seals, and this means that they will be somewhat less expensive. An example can be quoted of the surface sealing of contaminated fill in an industrial area where surface structures supported by deep displacement piles to bedrock are driven through the fill. Many geotechnical, legal and health and safety issues then arise. A possible sequence of capping construction, from the over-site granular layer, which also serves to support the piling rigs, down to the landfill is as follows:

Minimum 300mm/maximum 700mm compacted free-draining granular material
500g/m^2 geotextile protection membrane
Geonet drainage layer
1mm thick welded membrane
500g/m^2 geotextile protection membrane (low density polyethylene (LDPE) or polypropylene as an alternative)
100mm thick single-size granular gas layer, but with a synthetic geotextile as the preferred alternative.
Geotextile separating layer (for example, Terram)
Existing landfill regraded to the design falls (gradients) necessary for precipitation run-off, with any `soft spots' made up to level using granular material

Several comments of more general interest can be made on such a scheme of capping. In many countries the capping seal will experience a wider range of temperature gradients than will the basal seal. LDPE, and particularly VLDPE, is more flexible than HDPE, but without a significant yield point, and will behave in a similar manner to polyvinyl chloride (PVC) as a geomembrane cover material. It is much less susceptible to stress cracking because its crystallinity is lower than that of HDPE. However, it has rather less chemical resistance and is more prone to oxidation than HDPE. The former point is less of an issue at the cap, but the latter means that it must be well covered up. Further information on the subject of lining choice is given by Peggs (1993).

It is usually essential at the cap, especially where there is to be construction on top, to control the outgassing from the fill. This is achieved by the gas layer and the installation of suitable outlet ports to atmosphere. Even with CQA procedures it is unreasonable to expect that a 100mm granular layer can be maintained in thickness over a site that may be several hectares in area, and so there is always the possibility of the layer thickness being lost in places together with a resulting build-up of gas pressure within the cap. The synthetic alternative is to be preferred. It is also the case that the latter is less expensive than the former.

When calculating overall costs it is necessary to include such expenses as those involving seal connections to structures, accommodating settlements of the fill without imposing excessive stresses on the synthetic materials, and the constructions for drainage, manholes, and so on.

Figure 7 shows in cross section another rather complex top capping sequence that has been used. Here there is a single sealing membrane, which could be PVC rather than LDPE or HDPE, and four geotextile layers with drainage layers.

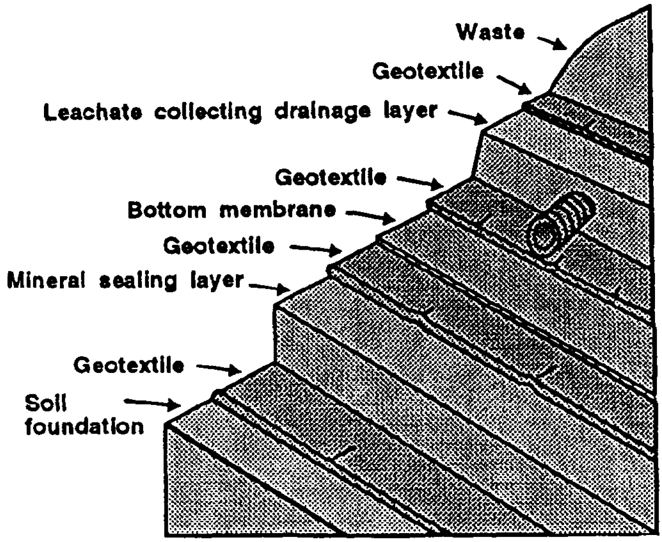


Figure 6 - Protection of bottom and sides of a waste disposal site

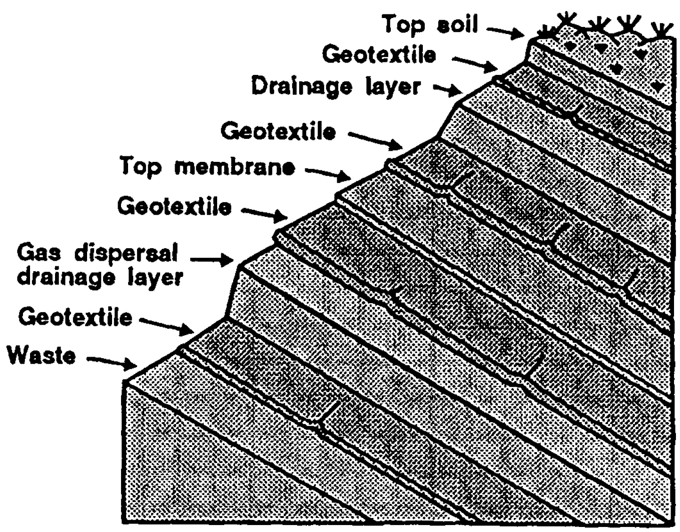


Figure 7 - Complex surface sealing using membranes, geotextiles and drainage layers

8 - SOME IMPORTANT CONSIDERATIONS IN LANDFILL CONTAINMENT DESIGN

- The importance of the need for third party (independent of the client and contractor) construction quality assurance (CQA) procedures, which would be formulated under ISO/EN 9000, cannot be over-emphasised.

- Slope stability analyses may have to be performed for the perimeter of the landfill site. The natural side slopes of some potential sites are of rock and are quite steep. These slopes may sometimes be sealed by raising a 3 metres, or thereabouts, clay barrier at the perimeter just in advance of the fill. Some infill sites may be in soil, in which case standard slope stability analyses will be performed using suitable computer software in order to determine a safe slope angle. For information on this subject reference may be made to Oweis (1993). Depending on the soil properties the design can probably be on the basis of peak shear strength parameters because in the longer term the slope will have lateral support from the waste infill. Also, if a plastic membrane is to be used on the soil slope then the soil contact surface of the plastic sheet should normally be textured (ridged) and its frictional characteristics with the soil determined.
  It will also be necessary to calculate the stability of the steep-sided clay bunds that divide a site into cells. The clay forming these bunds may be given geotextile support, and there will also be lateral support from the waste as the bund is raised with the level of the waste. Provided that geometrical, groundwater, and material strength information is available, then standard computer programmes can be used to do these analyses.

- Leachate composition may have an influence on a lining. The pH of waste decreases during the anaerobic acid phase. This increasing acidity is likely to increase the solubility of metals and thus their mobility. Sulphate is reduced to hydrogen sulphide. Humic materials are produced and they behave as natural chelating agents, so enhancing metal mobility. Carboxylic acids also act as chelating agents and there is evidence of metal concentrations in leachate as the waste becomes increasingly decomposed. Leachates having pH levels <3 or >11 are especially aggressive. Acids such as hydrofluoric and phosphoric can dissolve a soil, but soils do have a capacity to buffer acids at least in the early stages.
  As would be expected, the chemical make-up of a leachate changes as a function of time spent in the fill. Table 3 shows this compositional change. Further information on leachate composition may be obtained from Ehrig (1988) and on its interaction with soil from Fernandez and Quigley (1985, 1991), Bowders and Daniel (1987), Broderick and Daniel (1990) and Budhu et aL (1991).

- Liner hydraulic conductivity raises important issues, in particular the fact that leachate permeabilities and gas permeabilities differ for the same type of mineral seal. Also, the actual chemistry of the landfill, both as a function of waste type and time, can affect liner hydraulic conductivity especially if the leachate is highly acidic or basic or contains significant concentrations of organic chemicals, oils or List 1 substances.
  Maximum permissible hydraulic conductivity for a mineral sealing layer is 10^{-9}m/s and the typical permeability for an HDPE liner prior to installation is about 10^{-14}m/s. Flaws will increase this latter figure. Quite detailed assessments are needed but, based on Darcy's law, Figure 8 contains a very simple preliminary calculation of the transmission time through a somewhat substantial 3m thick liner and three leachate depths. The

cross-section in Figure 9 takes the UK recommended maximum leachate head of 1m, and only a 1m thick clay mineral liner and calculates the volume seepage per hectare per day. In the unlikely event that the leachate drainage performs so effectively as to remove all liquid above the liner, the hydraulic gradient under these conditions is unity irrespective of the thickness of the liner. It is then easy to calculate the annual volume seepage rate for the clay having a hydraulic conductivity of 10^{-9}m/s.

It is quickly realised that for a fixed leachate head (say 1 metre), the leakage rate decreases non-linearly with increasing thickness of liner. This means that there will be very little reduction in leakage rate, and therefore little practical advantage, to use clay soil liners having a thickness greater than 3- or 4-times the permissible 1m head of leachate.

Leachate transmission (breakout) time through a clay mineral liner may also be estimated in a preliminary manner from the equation

$$t = \frac{d^2 n}{k(d+h)}$$

where
t is the transmission time (seconds),
d is the liner thickness (metres),
h is the leachate depth above the liner (metres),
k is the liner hydraulic conductivity (metres/second), and
n is the porosity of the liner.

For example, let d = 1m, h = 1m, k= 10^{-9}m/s, and n = 0.3. Then

$t = 1^2 \times 0.3/10^{-9}(1 + 1) = 1 \times 0.3 \times 10^9/2 = 0.15 \times 10^9$ seconds = 4.76 years.

This very low result means that the clay liner must be supplemented with bentonite (ideally a GCL) and/or HDPE in order to increase the leachate retention time. The equivalent figure for a 3m liner thickness and a 1m leachate head is 31.8 years, which is still somewhat low and very conservative compared with the figure of 72.5 years from the Darcy calculation which does not include the porosity parameter.

Although, according to the current UK recommendation, the maximum allowable head of leachate in the landfill is 1 metre, in some cases the National Rivers Authority (the Government regulatory body) will allow a temporary leachate head of up to 3 metres in emergencies provided that it is pumped down as soon as practicable because, as demonstrated above, the leachate transmission time through the liner is substantially decreased if that head is allowed to rise. It is as yet unclear as to how this disadvantage would be offset in a non-cellular bio-reactor landfill by the presumed quicker stabilisation of the chemical leachate cocktail.

Liner uplift could develop if there is a high water table in the ground surrounding the landfill site. Figure 10 indicates that any high perimeter groundwater level must be lowered by well pumping, but that the pumping rates can be reduced as the downward (and lateral) forces on the liner increase with rises in the landfill. More generally, the presence of any water pressure at the ground-liner interface decreases the frictional resistance, an effect that could cause particular problems with a geomembrane liner.

Table 3

Typical composition of leachates from recent and old domestic wastes at various stages of decomposition (after the UK Department of the Environment, 1986)

Determinand	Leachate from recent wastes	Leachate from old wastes
pH	6.2	7.5
Chemical oxygen (mg/l)	23800	1160
Biochemical oxygen (mg/l)	11900	260
Total organic carbon (mg/l)	8000	465
Fatty acids (mg/l)	5688	5
Ammoniacal-N (mg/l)	790	370
Oxidised-N (mg/l)	3	1
o-Phosphate (mg/l)	0.73	1.4
Chloride (mg/l)	1315	2080
Sodium (Na) (mg/l)	960	1300
Magnesium (Mg) (mg/l)	252	185
Potassium (K) (mg/l)	780	590
Calcium (Ca) (mg/l)	1820	250
Manganese (Mn) (mg/l)	27	2.1
Iron (Fe) (mg/l)	540	23
Nickel (Ni) (mg/l)	0.6	0.1
Copper (Cu) (mg/l)	0.12	0.3
Zinc (Zn) (mg/l)	21.5	0.4
Lead (Pb) (mg/l)	8.4	0.14

. Liner leakage occurs, in both clay and plastic, as a result of degradation over a period of time that runs into decades. A clay liner breaks down due to the processes of cation exchange, leading to weaker bonding between mineral ions. Plastic liners will experience gaps caused by poor site control - unsuitable methods of delivery to the site, sharp stones cutting through when laid, breaks caused by plant on site or tools that have been dropped, and breaks in welds that have escaped detection. A few very small breaks can lead to substantial and increasing leachate losses during the lifetime of the site. USA EPA requirements include the use of a leak detection system capable of detecting a leak within 24 hours of its occurrence. In an American survey by Darilek et al. (1989a), who used a resistivity method to survey 28 completed liners for leaks, 542 leaks (0 - 72 leaks per site) with an average areal density of 26 leaks per hectare were found. Of these, 18% were found in parent material and 82% were in seams at details such as sump and pipe protrusions, which also included seams. Giroud and Bonaparte (1989b) also examined leaks and concluded that 1 defect per 10m of seam could be expected for geomembranes installed without third party QA and that an average of 1 defect per 300m of seam weld could be expected in the case of reasonably good installation practice and third party (independent) QA. For typical panel widths, seam defects are likely to result in 3 to 5 leaks per hectare with good QA. In a further study, Bonaparte and Gross (1990) examined leakage rates measured in the leak detection layer of double liner systems and concluded that in 19 geomembrane-lined landfills there was leakage through the liner.

Daniel (1993) gives examples (Table 4) of calculated flow rates based on: a 300mm head of leachate; a soil liner k value of 10^{-10}m/s (best), 10^{-9}m/s (average) and 10^{-8}m/s (worst); a geomembrane containing holes having an area of 100mm^2; and the number of holes per hectare being 2 (best case), 20 (average case) and 60 (worst case). This table demonstrates the clear advantages of a composite liner system, with leakage flow rates being typically at least 100-times less than those through a geomembrane or clay soil liner alone. In addition, even for a higher than recommended clay soil liner at a hydraulic conductivity of 10^{-8} m/s and with 20 holes per hectare in the geomembrane the calculated flow rate through the composite liner is much less than the flow rate through quite good quality clay soil liners or geomembranes acting on their own. Attempts should always be made to detect the location of leaks after a lining system has be laid down and before the waste is placed. Use, for example, of a geophysical electrical method can remove much of the uncertainty that would otherwise remain over the lifetime of the site.

Table 4

Flow rate as a function of liner flaws (after Daniel, 1993)

Type of liner	**Flow rate**		
	Best case	**Av. case**	**Worst case**
Geomembrane alone holes/hectare	2 500 2	25 000 20	75 000 60
Compacted soil alone k (m/s)	115 10^{-10}	1 150 10^{-9}	11 500 10^{-8}
Composite liner holes/hectare k (m/s) contact	0.8 2 10^{-10} poor	47 20 10^{-9} poor	770 60 10^{-8} poor

From Darcy's law, $v = ki$

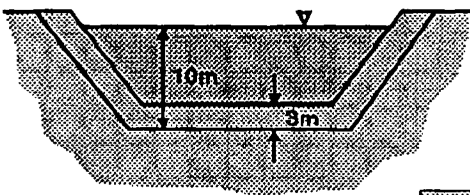
where v is the vertical velocity of the leachate flow through the liner

k is the vertical hydraulic conductivity

i is the hydraulic gradient equal to $\frac{h}{t}$

h is the head of leachate above the liner base

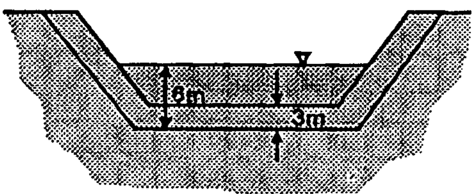
t is the thickness of the basal liner



7m of leachate above base

$$v = 1 \times 10^{-9} \times \frac{10}{3}$$
$$= 3.33 \times 10^{-9} \text{ m/s}$$
$$= 0.104 \text{ m/year}$$

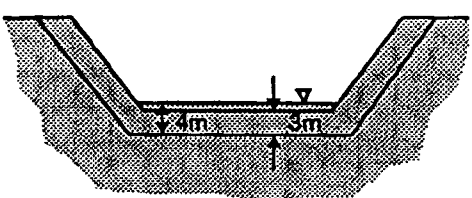
28.8 years to traverse the liner



3m of leachate above base

$$v = 1 \times 10^{-9} \times \frac{6}{3}$$
$$= 2 \times 10^{-9} \text{ m/s}$$
$$= 0.062 \text{ m/year}$$

48.3 years to traverse the liner

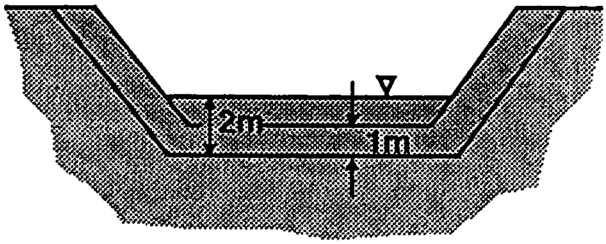


1m of leachate above base

$$v = 1 \times 10^{-9} \times \frac{4}{3}$$
$$= 1.33 \times 10^{-9} \text{ m/s}$$
$$= 0.041 \text{ m/year}$$

72.5 years to traverse the liner

Figure 8 - Movement of leachate through a 3m thick basal liner having a vertical permeability (hydraulic conductivity) of 1×10^{-9} m/s



The flow rate can also be expressed as a quantity.

$$Q = k\,\frac{(l + d)}{d}$$

where

Q = seepage rate ($m^3/s/m^2$)

l = leachate head above top of the liner (m)

d = thickness of the liner (m)

k = hydraulic conductivity (m/s)

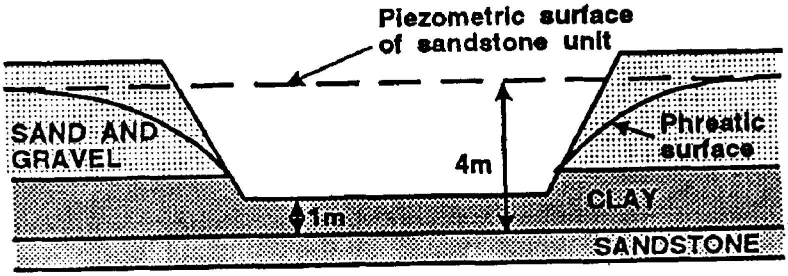
In this example, a mineral liner 1 metre thick having a hydraulic conductivity of 1×10^{-9} m/s and a leachate head of 1 metre yields a rate of seepage of 1.7 m^3/hectare/day.

Suppose that a very efficient leachate drainage system removes all the leachate above the liner. The hydraulic gradient is then unity (one) irrespective of the liner thickness. For a clay liner having a hydraulic conductivity of 10^{-9} m/s the annual volume seepage rate through the clay is

$$Q = 1 \times 10^{-9} \times 60 \times 60 \times 24 \times 365 = 31.5\text{mm/year}$$

$$= 315\text{m}^3\text{/hectare/year}$$

Figure 9 - Seepage through liners



Upward pressure at base of excavation $= 4m \times 9.81kN/m^3$

Downward pressure at base of excavation $= 1m \times 19kN/m^3$

Factor of safety against base heave $= \frac{19}{39.24} = 0.48$

Figure 10 - A simple section and calculation demonstrating the potential for base heave caused by a high water table

- Gas migration is a very sensitive subject for obvious reasons. Books have been written on the matter, but only one or two points are mentioned below.
  - As noted above, gas transmissibility exceeds that of a liquid.
  - The type of waste determines the methanogenic processes that will take place in the waste. Cellulose and hemicellulose are the principal biodegradable components of non-inert (sanitary) waste, these two constituents accounting for 91% of the methane potential of refuse. The rest of the methane potential of refuse consists of protein (ca 8.3%) and soluble sugars (ca 0.5%). The microorganisms responsible for the conversion of refuse to methane are sensitive to pH, the optimum pH for these organisms being between 6.8 and 7.4. Methane production rates decrease sharply at pH levels greater than about 5.
  - There needs to be a (statutory) legal distance between new buildings and a waste disposal site.
  - There must be gas monitors installed close to adjacent buildings.
  - On-site gas control and management schemes should be contained in the technical documentation.

- Diaphragm wall cut-offs can be important features of waste infilling schemes for two main reasons. First there may be a dilute and disperse site that is found to be dispersing too much leachate and not diluting it sufficiently. Second, following water sampling, a sealed site may be found to be leaking leachate. In both cases there is little that can be done for the base of the landfill site, but lateral migration of leachate (and of gas) can be intercepted by means of diaphragm walls, usually constructed in trench by a back-hoe and using bentonite for support during construction (see Figure 11). After reaching the required trench depth a reinforcing cage can be lowered and then a cement/pulverised

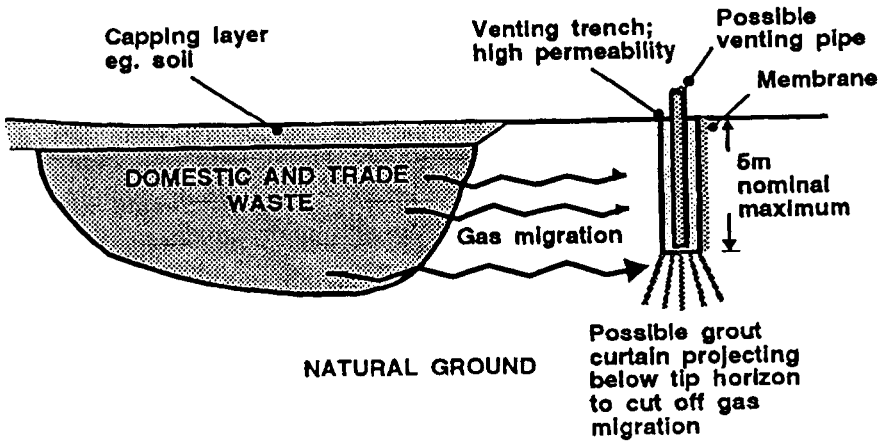


Figure 11 - Trench to intercept lateral gas migration

fluel ash slurry tremied in to the base. There are variations on this. For example, a plastic membrane can be incorporated into the trench (but there are welding difficulties), or a patented membrane system can be installed using a special framework. If, for whatever reason after construction, the trench and wall are not deep enough the effective depth of the cut-off can be increased by putting down boreholes from the base of the trench and then using permeation grouting.

It will usually be very expensive to construct a diaphragm wall around the whole perimeter of a landfill, but if the general direction of the groundwater flow (and gas flow) is known, or can be estimated from the geological structure, then a wall can be constructed over part of the site. Suitable leachate drainage and take-off facilities, together with gas venting systems would need to be incorporated.

9 - CONCLUSIONS

The following are just a few of the factors that are of special importance in this area of landfill design.

- Knowledge of the type and amount of waste, particularly whether it is hazardous waste.
- Careful assessment of the potential for groundwater and surface water contamination by leachate escape while the landfill is biochemically active because this will affect decisions on whether the site must be sealed.
- Substantial design and implementation of the sealing system, together with checks for leachate leakage, and of the waste infilling process.
- Implementation of third party CQA procedures according to ISO/EN 9000 during site sealing and site capping procedures.
- Installation of gas and leachate take-off systems.
- Gas and leachate monitoring, especially around dilute and disperse sites.

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VOTO DE AGRADECIMENTO

O Dr. Tocha Santos expressou, em nome das entidades organizadoras da 9ª Lição Manuel Rocha, o seguinte voto de agradecimento:

"A audiência teve o privilégio de ouvir uma conferência muito interessante sobre um tema da maior actualidade. Está relacionado com uma das maiores preocupações actuais de todas as comunidades a nível mundial - o depósito de resíduos. O resíduo é, actualmente, um sub-produto inevitável da nossa sociedade de consumo. Daí que um sistema de gestão de resíduos apresente dificuldades acrescidas que são proporcionais à dimensão e ao nível de desenvolvimento da comunidade envolvida.

Sendo os aterros o destino final mais comum dos resíduos, os aspectos de engenharia relacionados com o seu projecto, exploração, instrumentação, selagem e reutilização constituem importantes desafios para a sociedade geotécnica.

O conferencista, um professor universitário proeminente neste domínio de actividade, com uma experiência notável académica e prática como consultor de engenharia, conseguiu cobrir, num reduzido espaço de tempo, todos os importantes problemas relacionados com o tema, de uma forma clara e o mais compreensível possível.

Professor Attewell, com a sua lição, cada um de nós, académicos, consultores, engenheiros de departamentos governamentais e municipais, estudantes ou pessoas não técnicas, aprendeu com a sua experiência. Foi uma ocasião para realçar, mais uma vez, a importância da Geotecnia e, por consequência, dar a conhecer a sua contribuição positiva para a resolução destes problemas, às autoridades centrais e locais responsáveis pela gestão dos resíduos e à opinião pública. Apesar da existência de regulamentos, que consideram obrigatórias as medidas geotécnicas necessárias (que felizmente se encontram largamente difundidos nos países desenvolvidos), ainda existe muita actividade a ser desenvolvida, especialmente em relação a antigos locais de descarga de resíduos. Uma completa subordinação a estes regulamentos e a obtenção de recursos financeiros necessários para o estabelecimento de uma política adequada de tratamento e depósito de resíduos constituem algumas das acções necessárias para que seja possível permitir aos cidadãos uma boa qualidade ambiental.

Senhor Presidente, gostaria de terminar a minha intervenção, propondo um voto de sincero agradecimento ao Professor Attewell pela sua excelente lição, seguindo a tradição de qualidade das anteriores lições Manuel Rocha".