

11 THE TREATMENT OF CONTAMINATED SOILS

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11 THE TREATMENT OF CONTAMINATED SOILS

11.1 Introduction

11.1.1 Contaminated soil in Europe

In the latter quarter of the twentieth century there have been rapid advances in the development of techniques for the decontamination of chemically polluted soils and associated groundwaters. Environmental disasters, pressure group activity, and national governmental and European policies and legislation, have focused attention on the need for safe options for dealing with potentially toxic wastes and contaminated materials. Both soil and water have been identified as invaluable natural resources, which should be protected.

Contaminated soil presents a challenge to land reclaimers and developers, and the risks associated with the presence of potentially toxic chemicals in soil and water need to be removed in a manner that retains as much of the indigenous materials as possible. The need to retain uncontaminated material on site has led to an increase in the use of methods to decontaminate soils and groundwaters instead of using engineered systems of removal, burial or containment.

In the European Community there are many thousands of sites which are known to have been contaminated by industrial activities. In Germany alone, for example, there are thought to be between 70,000 and 90,000 contaminated sites,³⁵ a significant proportion of which are associated with coal and steel production and processing.

Each country has its own approach to the classification and treatment of contaminated sites, and to waste management and disposal practices,¹⁰² although current trends are towards a common approach, where waste producers, site owners and central and regional governments have increasing commitments towards the avoidance and clean-up of contaminated land.

11.1.2 The options available

The activities of the coal and steel industries have produced a diversity of potential chemical soil contaminants, as has been established in earlier chapters. Soils are themselves highly complex media, often displaying great variation in chemical, physical and biological characteristics. No one technique for the remediation of contaminated soil is therefore ever likely to be applicable to more than a relatively small proportion of all contaminated land situations. At many contaminated sites a combination of remedial techniques is often the most appropriate way to deal with contaminated material.

It is a primary objective of those responsible for the reclamation of sites containing toxic materials to ensure not only that these materials are dealt with in such a way as to reduce risk, but also to implement schemes that aim to conserve uncontaminated natural materials as far as possible. The treatment of contaminated land has thus undergone a change in emphasis in order to:

- reduce the amount of toxic materials being dealt with by confinement in terrestrial repositories;
- increase the separation of contaminants from the matrix which they are polluting, so reducing the volumes of waste generated, and conserving soil and water.

In any reclamation operation there are site specific constraints such as the availability of materials, the location, area and topography of the site and, of course, cost. Such factors as these define, at an early stage in the design, the methods that may be applicable to the site.

The methods available divide broadly into:

- traditional methods of isolation or removal of contaminated materials;
- decontamination techniques which remove contaminants from soil and water.

The types of isolation and removal techniques available are outlined in Table 11.1. Figure 11.1 shows the range of treatments for contamination that are available, and their applicability to various target contaminants. Decontamination treatments can be broadly divided into three categories for soil and two for water, as illustrated in Figure 11.2.

Table 11.1: Typical options for the isolation and/or removal of contaminated ground

Method	Characteristics
Isolation	
Capping	Impermeable layer covering the contaminated ground to reduce rainfall infiltration.
Vertical barriers	Impermeable, vertical, subterranean barriers to minimise migration of contamination and pollution movement in groundwater.
Diversion trenches	Drainage systems to intercept water and/or pollution from contaminated ground.
Break layers	Layers of single-sized stone above saturated zone of contamination to prevent upward movement of contaminants by capillary action.
Horizontal barriers	Impermeable barriers beneath waste or contaminated ground to reduce downward movement of contaminants.
Removal	
Excavation	Physical excavation of contaminated ground and removal to a suitable landfill or treatment plant.
Total containment	Excavation of material and replacement in a purpose built impervious cell.

Target compounds	Treatment technology	Vapour extraction	<i>In situ</i> bioremediation	<i>Ex situ</i> bioremediation	Soil washing	Containment	Stabilisation/solidification	Thermal treatment	Vitrification	Solvent extraction	Pump and treat	Leaching
Metals (fines and soluble)		✗	✗	✗	✓	✓	✓	○	✓	✗	○	✓
Metals (larger particulate)		✗	✗	✗	✓	✓	✓	✗	✓	✗	✗	✗
Volatile organic compounds		✓	✓	○	✗	✗	✗	○	○	✓	✓	✗
Semi volatile organic compounds		○	✓	✓	✓	✗	✗	✓	○	✓	✓	✗
Halogenated organics		✓	○	✓	✓	✗	✗	✓	○	✓	✓	✗
Oil hydrocarbons		○	✓	✓	✓	✗	✗	✓	✗	✓	✓	✗
Coal tars		✗	○	○	✓	✓	✓	✓	✗	✓	○	✗
Asbestos		✗	✗	✗	✗	✓	✓	✗	✓	✗	✗	✗
Coal		✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗
Dioxins		✗	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗

✗ : Inappropriate in most cases

✓ : Appropriate in many cases

○ : Of some potential under certain circumstances

Figure 11.1: Target contaminants of soil and groundwater, and the treatment technologies appropriate for these contaminants

Contaminated land

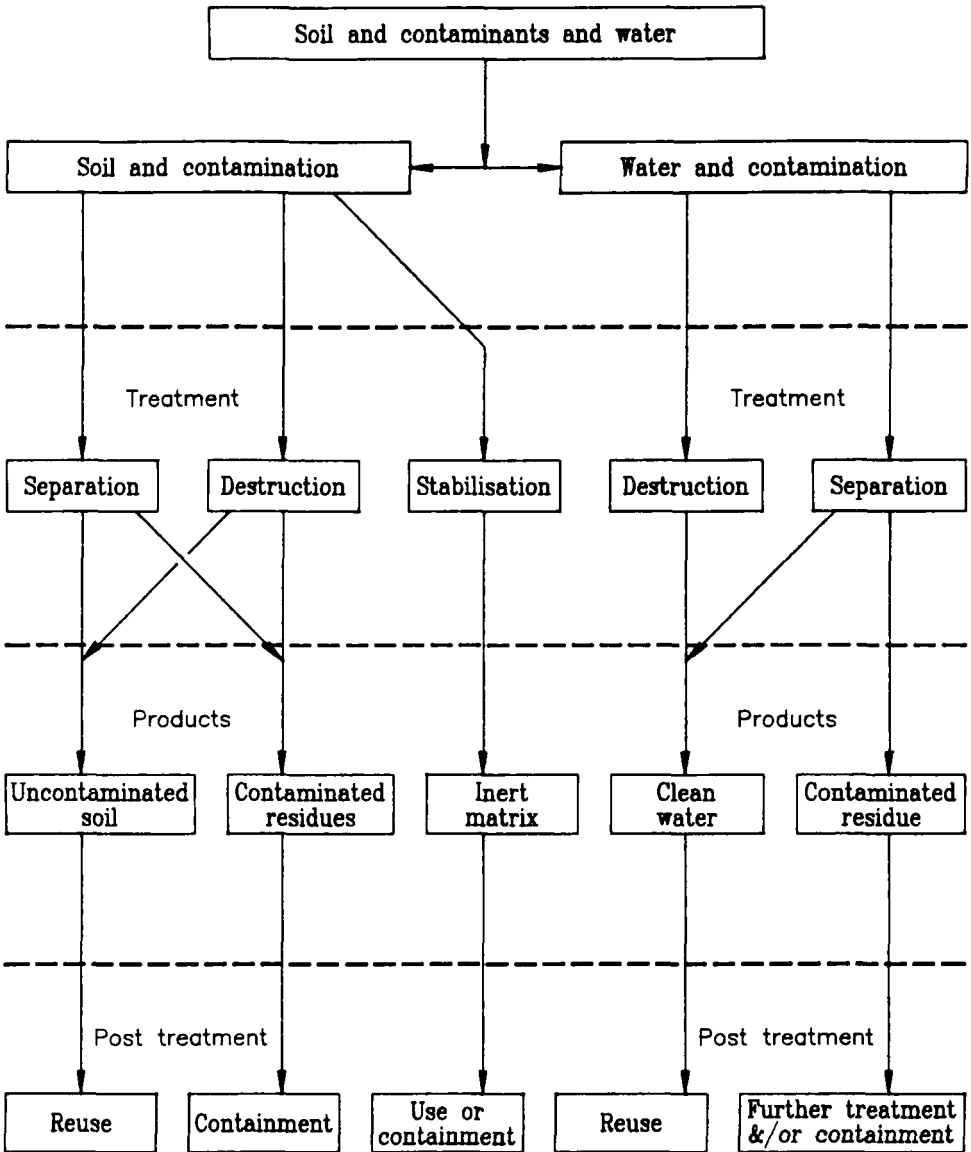


Figure 11.2: Application of treatment technologies to contaminated materials and the implications for product formation and further treatment

Whether a decontamination treatment rather than more traditional techniques is applicable is affected by:

- the nature of the contamination present;
- the nature of the soil materials present;
- target concentrations required after decontamination;
- the volume of materials to be treated;
- site size and access;
- availability of technology locally;
- cost effectiveness of decontamination treatment compared with excavation and containment techniques;
- willingness of the reclamation team to use new and emerging technologies.

The various techniques available for treating contaminated soils are described in subsequent sections as follows:

- removal and disposal of contaminated materials;
- *in-situ* isolation;
- cover systems;
- grouted horizontal barriers;
- thermal techniques of decontamination.

11.1.3 European Community Directives on waste

The creation and treatment of contaminated materials in the European Community is addressed within the Council Directive on waste (75/442/EEC), originally implemented in 1975, and subsequently amended in 1991 (91/156/EEC). This Directive recognises the following important points:

- waste disposal must aim to protect human health and the environment from damage during the collection, transport, treatment, tipping and storage of wastes;

- recovery and recycling of materials is encouraged, including composting and biological treatments;
- trade and competition in waste handling operations should not be affected where disposal is necessary;
- systems involving the use of permits should be implemented to control the storage, tipping and treatment of wastes on behalf of third parties;
- the principle of the 'polluter pays' *i.e.* polluters will pay fines and/or clean-up costs, is established.

Within the Waste Framework Directive the following Articles are of particular relevance to contaminated soils and residues encountered at steelworks, colliery and coal carbonisation sites:

- Article 3 promotes the use of waste as a source of energy, and the recovery of materials from wastes during reclamation;
- Article 4 promotes the use of safe methods of disposal or recovery in order to protect soil, water, air, plants and animals;
- Article 5 requires the setting up of a network of disposal installations which takes account of the 'best available technology not involving excessive costs'.

The following sections within this chapter outline some of the technologies indicated in Article 5 of the Waste Framework Directive, and the ways in which these can be used to overcome the risks associated with contaminated materials, during the reclamation of coal processing and steelworks sites.

11.2 Removal and disposal of contaminated materials

11.2.1 Landfill - past and present

The removal and disposal of materials to landfill should be considered in reclamation design for two reasons:

- past landfill practices at industrial sites often entailed burial of wastes within or near to the site. In this case landfills can be encountered as obstacles to reclamation at a given site, notably in terms of ground stability and potential contamination;
- landfill is an option for the disposal of contaminated materials arising during the course of a reclamation scheme.

A reclamation scheme may involve the design and construction of a new landfill at the site itself, in order to dispose of unwanted or difficult materials, or such materials may be transported off-site to existing landfill facilities.

Whilst this chapter deals with the techniques of ground treatment, and thus the use of landfill as a means of disposal rather than an obstacle to reclamation, the following review of landfill technology will serve to illustrate factors that will influence the impact of old landfill sites on a reclamation operation.

11.2.2 Hazardous waste landfilling in Europe

The only universal option for eliminating risk from the presence of contaminated materials at a given site is by physical removal of the materials by excavation. This has been widely practised throughout Europe in the past, and will continue to be used. Nevertheless, many countries which are densely populated *e.g.* the Netherlands, and/or lack deep soils and natural depressions above bed rock *e.g.* Finland, have restricted space suitable for landfill. These factors, together with the move towards decontamination technologies, have led to a decline in the

availability of landfill space. In the Netherlands, for example, where a rigorous policy of soil protection and decontamination has been implemented, only one landfill remained for the disposal of toxic materials in the early 1990s. The price of such disposal is high.

The removal from a site of the toxic material posing risks to the environment, human health or other targets may therefore remove the potential hazards but the transport of such materials simply transfers an equal or greater risk to another site if care is not taken to properly confine or treat the material. In many countries, hazardous wastes such as contaminated soils arising from former coking works sites, are removed to special landfill sites, where provision has been made to control the movement of toxic chemicals outside a defined area. Such controlled landfills are however relatively new facilities, and many countries either have no such landfills available, and/or possess a legacy of hazardous waste landfills where the precautions taken to avoid contamination of the surrounding ground were inadequate. In Italy, for example, a number of illegal hazardous waste landfills have been discovered in the Liguria region, where there is a shortage of landfill sites licensed to accept controlled wastes.¹⁰

The unspoken tenet of controlled hazardous waste landfilling is that the materials so deposited will remain in a confined volume of ground for ever. No guarantee can be given with any degree of confidence that this will be so, because landfills and underground repositories are generally not failsafe (see Box 11.1). Many landfills only have design lives for sub-surface containment in the order of 20-30 years. Thus, with existing technologies for landfill design, and the often incomplete chemical screening of materials prior to disposal, no landfill operations are risk-free.

The precautions taken to control the movement of hazardous substances, and thus reduce the risks associated with the new placement of materials in landfills, are reflected in the relatively high price paid for the tipping of material. The lack of alternatives have maintained landfilling in the

Box 11.1: The concept of the terms 'design life' and 'failsafe'

The 'design life' of a structure refers to the time within which it will satisfy the criteria with which it was designed to cope. In the case of an engineered system of containment for contaminated materials, this means the time within which the system will, with a high degree of statistical probability, maintain its integrity. A 'failsafe system' incorporates means of detecting failures of a containment at an early stage so that corrective action can be taken prior to a pollution incident.

waste management market place, although this situation is changing in the face of new technologies. It is because of price advantage and the large volumes of waste being produced that disposal to landfill is still, quantitatively, the most important form of toxic waste management in the world.

11.2.3 Containment practices

Landfills are often created in areas of natural or Man-made ground depressions. In the past little attention was paid to the nature of the natural geology of these areas, and thus landfills are found in geological materials that are totally unsuitable for the retention of liquid or gaseous materials within the body of the fill. Pits where sand and gravel were once extracted, for example, have become sites for the tipping of toxic wastes, with the consequence that leachate and gas are able to migrate through the permeable strata, sometimes over considerable distances, leading to the pollution of previously uncontaminated land or bodies of water.

Clearly, a waste landfill, particularly that for toxic waste, must be located so that migration and pollution are minimised. Therefore, these tips

should be sited in relatively impermeable ground, such as in stiff clay and, if newly constructed, should include the following design features:

- impermeable lining materials;
- peripheral monitoring wells for groundwater and gas sampling and analysis;
- provision of leachate collection facilities within the body of the landfill;
- gas venting or collection measures;
- adequate surface drainage features.

In addition to these design features there should be tight control exercised over the wastes that are deposited. Thus, sites should be licensed to receive only certain types of compatible wastes, and should be operated by the owner in such a way as to ensure that this is adhered to. In the past, in countries operating site licensing schemes for hazardous waste disposal, such as the United Kingdom and Germany, there have been serious breaches of landfill licence conditions, leading to later pollution and site restoration problems. A landfill operator may be prosecuted for the breach of such conditions.

Landfills are chemically and biologically active structures during the course of their operation, and usually for a period of many years after the tipping of wastes has ceased.

11.2.4 Landfill gas and leachate

Whether a landfill operates under strict control or not it is likely to contain a variety of materials derived from different sources. These materials, depending upon their physical and chemical components, will interact both with each other and with a variety of associated microorganisms. These interactions make the accurate prediction of the life cycle and environmental impact of a landfill difficult to achieve.

In general, two products of the microbial decomposition process are of concern at landfill sites:

- landfill gas, likely to contain carbon dioxide, methane and possibly other toxic, asphyxiant and inflammable gases and vapours;
- leachate, deriving from water entering the landfill and other liquid, soluble and suspended wastes (and degradation products) of varying toxicity and corrosiveness.

It is these two products of the landfill process that make the provision of adequate containment and control measures such a critical issue at actively gassing landfill sites. Such measures may include, in addition to containment systems, gas venting, gas pumping and combustion, and leachate pumping for recirculation, disposal or treatment.

11.2.5 Reclamation and disposal

In the case of disposal to landfill as part of a reclamation scheme, it is often left to a works contractor and landfill operator to ensure the safe disposal of contaminated wastes. It is however the responsibility of those in direct control of the reclamation scheme to ensure that the disposal of the wastes is in the hands of organisations that are applying the following criteria:

- adequate chemical characterisation of the waste prior to landfilling;
- strict health and safety precautions for those handling the materials between excavation and disposal;
- disposal of the wastes to a landfill that is of suitable design quality, to ensure proper containment of the materials, with the necessary waste disposal licensing.

The design and operation of an on-site landfill during the course of a land reclamation scheme should conform to similar criteria. The choice of

landfill design will be dependent on the nature of the site, the development plans and the type of materials to be contained. The latter will particularly influence the choice of Man-made polymers that may be used to line the landfill, which could be adversely affected by organic constituents of toxic waste from, for example, coal carbonisation by-product residues. The manufacturers of such geosynthetic polymers should provide information and data on the use of these materials in chemically disturbed conditions, and materials without the correct specification should not be used.

11.3 *In situ* isolation techniques

11.3.1 Barriers to pollution

Where contaminated materials are present at a site, there may be the potential for containment of the contaminants without recourse to excavation.

A variety of techniques are available to isolate adjacent ground from contaminated materials. These techniques usually take the form of a vertical barrier, incorporated after the excavation of a deep trench.

Vertical barriers have limited applicability because they can only prevent lateral movement of contaminants. Such barriers are suitable for use where an impermeable material *e.g.* rock or clay, exists immediately below the waste, and there is the potential for placing vertical barriers around the waste to the depth of the impermeable material. However, in such situations a perched water table may be created within the contaminated ground, resulting in contaminated water at or near the surface, and waterlogged and unstable ground.¹³ Such situations can be treated with biological soil and groundwater decontamination techniques (discussed further in Section 11.8).

Materials and techniques used in the construction of vertical cut-off barriers include:

- geosynthetics and associated polymer sheeting;
- sheet piles, and associated displacement barriers;
- slurry and grouted walls;
- open or gravel filled trenches with incorporated drainage and leachate collection facilities.

Figure 11.3 shows a vertical barrier system which uses a geosynthetic membrane.

11.3.2 Geosynthetic membranes

Proprietary synthetic membranes, with specifications geared towards their use in contaminated materials, are available from a variety of sources. They are often available in rolls of sheeting, with appropriate bonding materials to seal joints together. Many of these materials are plastic polymers, which, although durable, are prone to tearing, puncturing and abrasion. Such membranes should therefore be installed so that they are in contact with materials which will not puncture them and which will protect them against damage. These materials include gravel, sand or bentonite clay.

Detailed design of vertical barriers must take into account the practicality of installing geosynthetic membranes. A system which is easy to install will minimise the potential for damage to the isolating barrier material.

The careful supervision of installation of geosynthetics is essential in order to ensure the integrity of the finished vertical barrier. A badly installed confinement system may produce no better control of pollution migration than existed before installation, and may even lead to worse problems occurring locally.

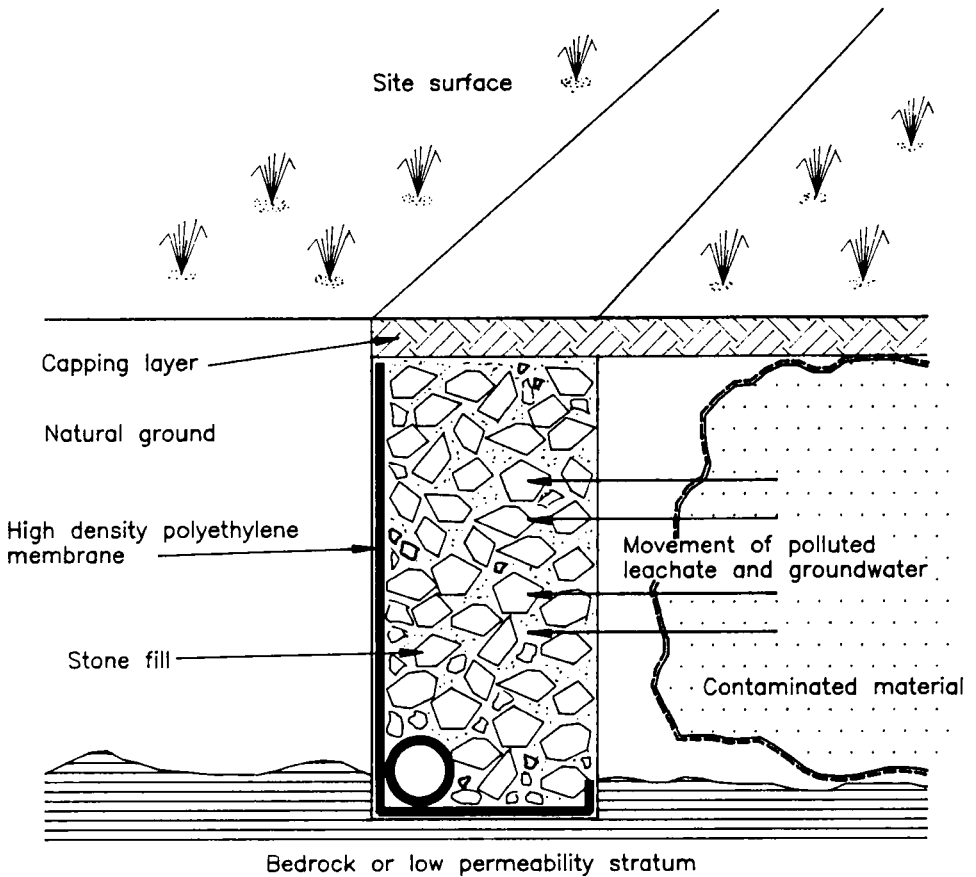


Figure 11.3: Cross section through a typical deep vertical barrier system, using high density polyethylene sheets

To ensure that geosynthetic lining material are impervious when laid damaged sheets must be discarded and seams checked for leaks. Various methods to test the latter are available *e.g.* ultrasonic and conductivity meters.

11.3.3 Sheet piles

Sheet piles, whilst being more robust than geosynthetics, are considerably more expensive. Piles can generally only be pushed into soft ground if there are no obstructions. They are therefore usually vibrated into the ground using special equipment.

Sheet piles fit together by their shaped, interlinking edges, and are not normally completely water tight, unless used in combination with other materials. Whereas sheet piling has been used for the confinement of contaminated materials, it is not generally the most suitable method, because of the permeability of the piles to liquids and their high material and installation costs.

Piling may be used to facilitate the installation of other barriers. For example, steel piles may be inserted and withdrawn, whilst, at the same time a cementitious grout is injected into the piled void.

11.3.4 Slurry walls and grouted barriers

Slurry walls can be used as barriers in situations where gas and leachate migration from landfill requires control.

The installation of slurry walls involves the excavation of a trench, which is accompanied by simultaneous filling of the trench space with a slurry (see Figure 11.4). The slurry prevents the collapse of the sides of a deep trench. The trench may be filled either with the final slurry compound or with a temporary support slurry which is then replaced by displacement with an alternative slurry which sets to form the barrier. During the placement of slurry materials, air spaces must not form if the final structure is to adequately control contaminant migration.

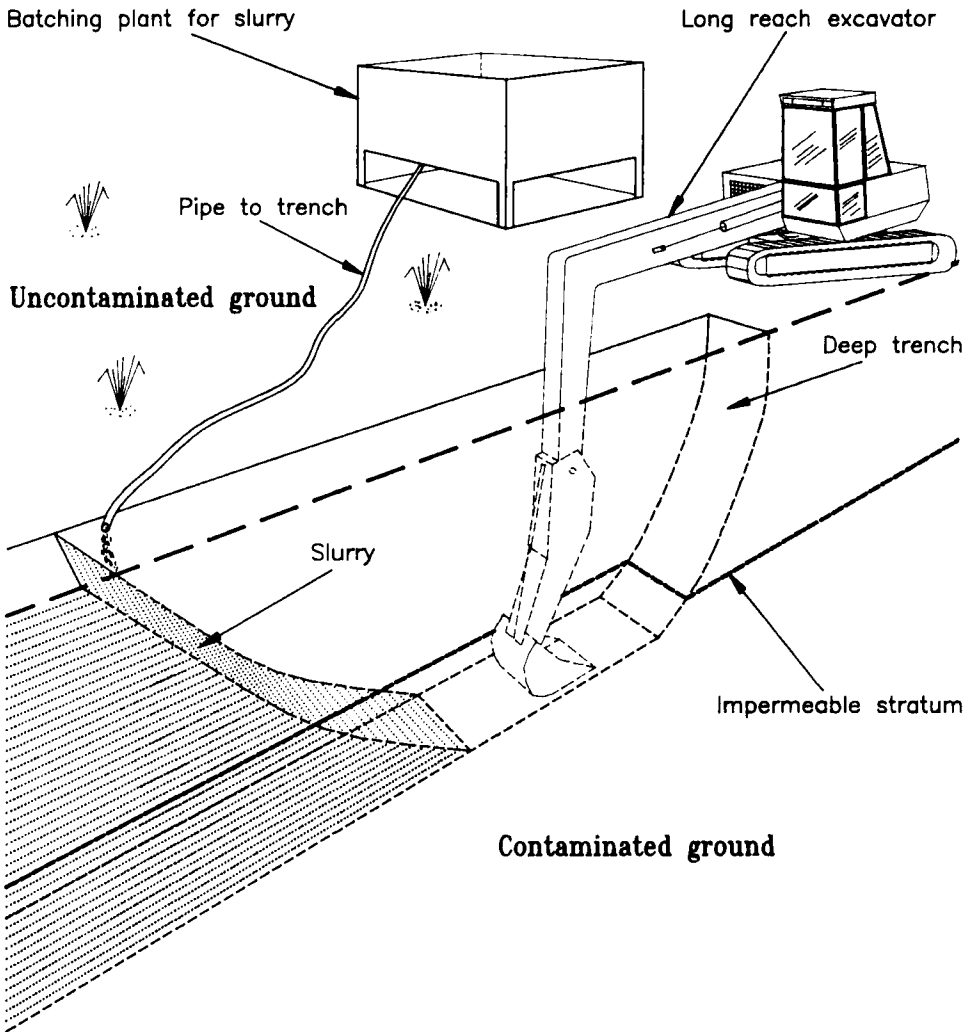


Figure 11.4: Construction of a slurry wall for vertical containment of polluting materials

Slurry materials may include clays (such as bentonite), clay-soil mixtures and clay-cement mixtures. New slurry materials and high density, hydrophobic compounds increase the number of options to be considered. The success of a barrier is determined by its final permeability and integrity. Permeabilities may be expected to be in the region of those for stiff clays ($< 10^{-9}$ m/s).

Grouted barriers can be introduced behind a high pressure air or water jet or, alternatively, directly into the ground. The grout saturates voids and fissures to reduce lateral permeability.

Future developments in this field are likely to include methods to confine contaminated materials within the ground by the use of *in situ* vertical and horizontal cut-off materials. Such techniques may include the *in situ* formation of impermeable polymeric compounds by the injection of polysaccharides mixtures. Similarly, the stimulation of the growth of soil microorganisms, and the associated formation of cellular material and polysaccharides within soil pore spaces, could provide a means by which the permeability of soil materials may be reduced.

11.3.5 Trench systems

In some instances the construction of relatively simple trench systems for intercepting pollution as liquid leachate or gaseous emissions, can be efficient and cost-effective solutions to pollution problems.

Trenches have often been used around the perimeter of actively gassing municipal landfill sites. These trenches intercept gas migrating towards adjacent ground and vent it to atmosphere in a controlled manner, via the path of least resistance. Such passive venting trenches are usually gravel filled, and incorporate a drain at the base to divert infiltrating rainfall and run-off water towards a sump, thus avoiding the accumulation of water within the trench. Gravel-filled trenches may be covered to prevent the infiltration of fine-grained particulate matter into the trench, and venting

pipes installed through the cover material to allow the release of gases to the atmosphere.

In a similar fashion, gravel-filled or open trenches containing a drainage system and sump can serve to control the migration of leachate from areas of contaminated wastes (see Figure 11.5). Trenches such as these have been used to avoid pollution breaching site boundaries in shallow ground. Leachate passing into a drainage collection system may be removed by the incorporation of a simple collection sump from where contaminated fluids can be pumped into containers for disposal or treatment off-site. Alternatively, leachate can be diverted to an on-site treatment plant; for example a biological reactor.

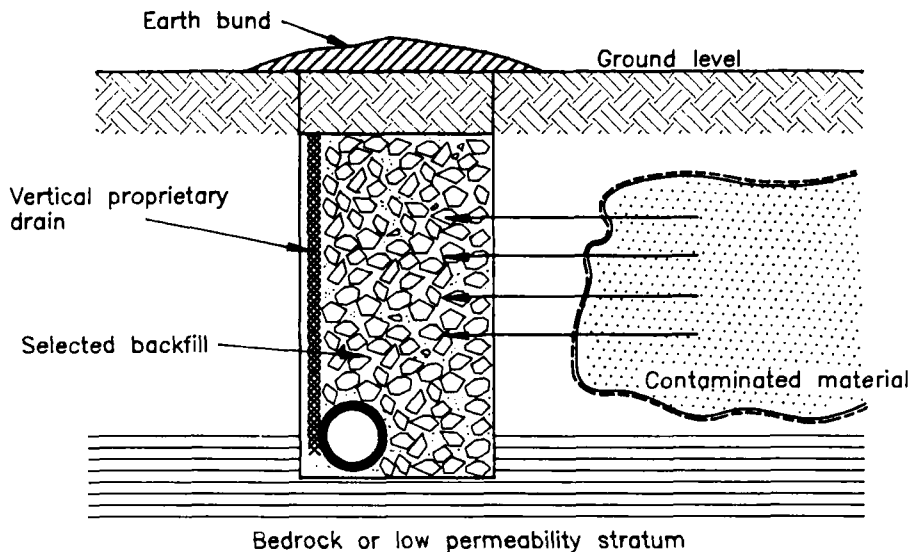
11.3.6 Costs versus effectiveness

The costs of piled, grouted and slurry barriers can be high, especially in ground requiring the construction of deep barriers. In addition these methods may not always be completely reliable, and can have design lives that are limited by the corrosive effects of the substances that they are designed to contain.

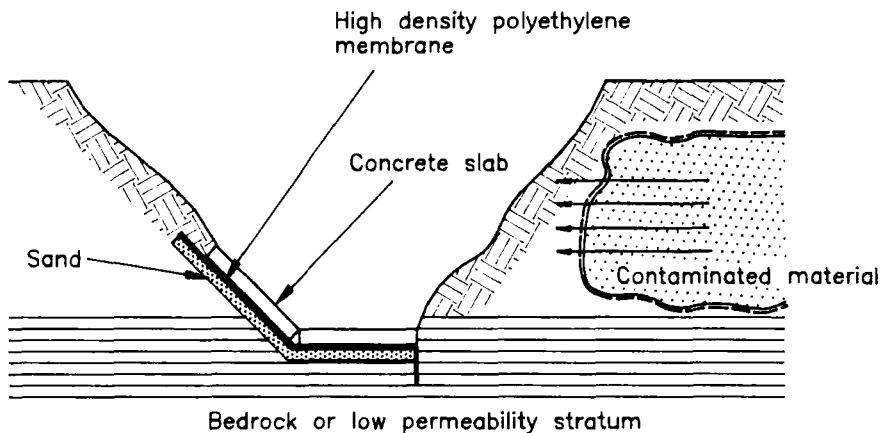
The most effective designs are often those which integrate two or more systems. An example of this would be the incorporation of a polymer sheet membrane within a slurry wall.

The high capital cost of integrated systems may be offset by their longevity compared to single systems.

The choice and correct installation of the most suitable materials is crucial to the successful implementation of a barrier system to control pollution. The costing of a barrier scheme should always allow for long-term monitoring in order to detect any failures of the system (see Box 11.2).



(a) Filled trench



(b) Open trench

Figure 11.5: Examples of cross sections through shallow filled and open trench systems designed to control the migration of pollution

Box 11.2: Cost considerations in the design of containment systems for pollution control

The costs of implementation of physical containment systems, including vertical barriers and cover systems, include many features other than those relating to civil engineering construction and materials. Management costs may include:

- weed control in trenches;
- vegetation management above a containment to avoid deep-rooted species;
- drainage pipe and channel clearance;
- emptying of drainage collection sumps.

Monitoring costs may include:

- installation of borehole stand pipes;
- periodic sampling of stand pipes for gas, groundwater or leachate;
- chemical analysis of samples;
- documentation of monitoring results.

11.4 Site cover systems

11.4.1 Introduction

One of the most frequently used methods of dealing with contaminated land has been by the covering of materials with a low permeability or impervious capping layer. These methods must however fully consider the containment and/or interception of contaminated materials below ground level, as cover systems only restrict movement of materials through the ground surface, and not laterally or below the contaminated ground. The advantages of capping a site are that:

- infiltration of rainwater and/or other liquid inputs *e.g.* flood waters, through the materials is reduced;

- the capping layer forms a barrier between users of the site and the contamination beneath;
- the need to remove contaminated materials from site or to treat them is deferred.

The use of high permeability break layers can assist in the prevention of upward capillary movement of buried contamination towards the surface of the ground.

Cover systems are used for dealing with contaminated land in housing areas in the Netherlands.¹⁵⁵ The need to reduce excavation and removal of contaminated ground for environmental and cost reasons is often a stimulus for the use of cover systems.

Any covering system is likely to include the following elements:

- sealing system *e.g.* clay;
- surface substrate *e.g.* top soil;
- gas control and drainage layer;
- vegetation cover *e.g.* grass, (where applicable);
- long-term management.

In the case of horizontal systems for the control of vertical movements of liquids, attention must always be paid first to the characteristics of the site in relation to groundwater movements and, particularly, changes in levels. In addition, following the implementation of a system, a strategy for monitoring the site is required in order to assess the integrity of the cover, so that any breaches can be detected and repaired quickly.

11.4.2 Capping layer

Capping materials

One of the most critical issues in constructing capping systems is that of the permeability of the materials used. Clay has often been used as a cap

material due to its low permeability, high plasticity and moisture retaining properties. Clays vary greatly in structure and properties however, and care should be taken in the construction of new clay caps so that only clays which have low and homogeneous permeabilities are used. The use of such clays will ensure adequate containment of the materials beneath, whilst substantially reducing the infiltration of water from the surface.

Similarly, the installation of a clay cap must be undertaken with adequate compaction, in order to avoid the incorporation of air spaces and breaches of the continuity of the material. A good quality, low permeability clay, will not be effective if the material is incorrectly or too thinly laid. Clay capping layers are usually required to have a permeability of 10^{-9} m/s or less.

If site conditions permit and materials are readily available, covering systems should incorporate a levelling layer of placed material, so avoiding major disturbance of underlying contaminated ground. The use of a levelling layer can reduce irregularities in site topography facilitating the placement of further layers of the capping system. Figure 11.6 shows an example of a cover system incorporating a clay cap.

Clay layers should be laid to agreed tolerances, so that a minimum depth of clay can be guaranteed. This is achieved in practice by using levelling markers at regular intervals across the site, and using these to guide the placement of clay. The final levels on the clay surface, and the falls that are allowed, should aim to avoid ponding at the surface during periods of rainfall.

Within levelling layers gas and drainage control measures can be incorporated.¹⁰⁷ These can divert gas and leachate away from the contaminated ground beneath the cover, and from the site surface, to areas where they can either be released or treated.

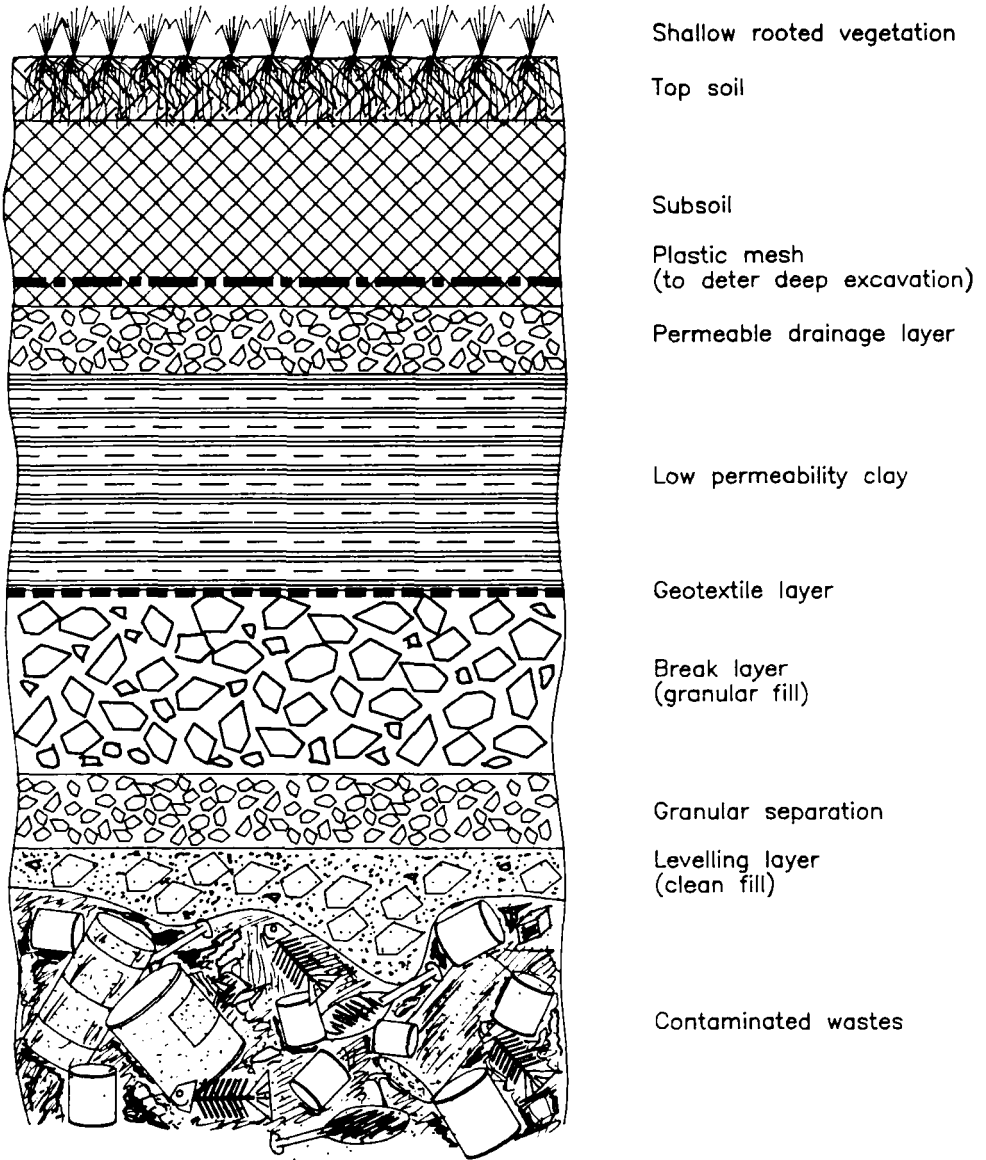


Figure 11.6: Example of a cover system for contaminated ground incorporating a clay cap and break layer (not to scale)

Breaches of capping structures

Clay should always be kept damp during placement, and should remain damp during the design life of a cap, to avoid desiccation and cracking. The latter is usually achieved by placing an adequate layer of clean soil above the cap. In addition any capping material that has the potential to fracture must be used with due attention to the possibilities of ground movement. In areas where differential settlement *e.g.* newly completed landfills, or intense geological movement *e.g.* earthquake activity, is likely, capping may not achieve the required degree of robustness. In such cases, fractures can lead to seepages of contaminated liquids and gases, and the need for remedial measures.

Similarly, breaches of caps can occur through the action of plant roots or burrowing animals. Accidental excavation of capping strata can be avoided by the use of warning grids buried above the cap (see Figure 11.6).

The use of artificial lining materials such as high density polyethylene, can improve the durability of a sealing system and may be used with or as an alternative to clay liners. The comments in Section 11.3.2 regarding the choice of geosynthetic membranes also apply here.

11.4.3 Break layers

The incorporation of stone, gravel or rubble into a cover system can improve performance by forming a stratum through which capillary action cannot occur (see Figure 11.6). Even in the best laid clay-sealed covers upward movement of soluble or liquid contaminants can occur through micropores in the capping layer, and thence through the cover soil, by capillary action. By maximising the spaces between the particles in an artificially created, competent ground layer, capillary movement can be minimised, so reducing the risk of upward contaminant migration.

Such break layers should lie above the highest ground or perched water level, and consist of material that is not prone to erosion and fracturing. Good quality materials, such as hard rock fragments, rather than mixed building rubble of non-uniform or uncertain composition should be used to ensure that degradation of the break layer does not occur. Material of a single particle size will give most void spaces. In addition, geotextile fabrics can be used to avoid clogging of break layers by the infiltration of fine-grained particles from the upper layers of the cover system.

11.5 Grouted horizontal barriers

Vertical barrier systems of containment have been discussed in Section 11.4. If there are no naturally occurring horizontal barriers beneath a contaminated site there are options for creating such barriers at depth using grouting techniques.

These methods are generally both difficult and costly to apply. The techniques fall into three categories:

- jet grouting;
- chemical grouting;
- claquage grouting.

These methods are summarised in Box 11.3.

11.6 Total containment

In circumstances involving small volumes of contaminated ground, it may be possible to excavate material and replace it within a purpose-built containment cell. Such a cell may be constructed of clay or bonded geosynthetic sheeting with adequate provision for drainage around the contained volume. This option avoids transport of contaminated materials off site, but requires a programme of long-term monitoring, due to the

Box 11.3: Horizontal grouting techniques

Jet grouting uses high pressure, water jets to cut voids in ground, which cement and bentonite slurry is then used to infill, in order to create a barrier. The technique relies on the stability of ground above the created voids and the nature of the ground removed under pressure.

Chemical grouting is designed to fill void spaces in existing ground. Thus, slurry is pumped into the ground in the region of treatment *e.g.* adjacent to or within contaminated soil or buried materials.

Claquage grouting uses high pressure grout injection to cause fracturing of the ground prior to grout infiltration.

possibility of containment damage and the limited design life of the system (see Box 11.1).

The option for total containment will be limited by the qualities and types of contaminated materials involved, and by local soil and groundwater conditions. In addition, the nature and location of sub-surface containment cells must be well documented and protected in order to avoid accidental disruption at a later date *e.g.* during subsequent site redevelopment.

11.7 Thermal techniques of decontamination

11.7.1 Types of thermal treatment

Contamination by most organic and some inorganic compounds within soils and slurries can be largely destroyed by thermal treatment. Thermal treatment techniques fall into three broad categories:

- incineration;
- two-stage thermal treatment;
- vitrification.

Thermal treatments in general are useful disposal techniques for materials that are contaminated with highly toxic chemicals which are not separable, recoverable or treatable by other means, and which present too great a risk to be contained within a landfill or other containment system. Such compounds may include highly chlorinated hydrocarbons, such as PCBs.

Solid residues from thermal treatments, including bottom ash and fly ash, cannot be treated as inert waste until fully chemically characterised, as they may contain high concentrations of heavy metals and toxic combustion products. Some metals and other inorganic substances, such as mercury, arsenic, lead and cyanide may, however, volatilise during incineration, and therefore not remain at high concentrations in the solid residues. However, if emission control measures are not taken such volatilisation transfers pollution to the medium of air.

11.7.2 Incineration

Total incineration destroys not only the contaminant but also the structure of the contaminated matrix. In the case of soils particularly, incineration therefore constitutes a destructive technique for decontamination which takes no account of the retention of soil structure and function.³⁵

Most European countries operate large incineration facilities to handle special wastes, including contaminated soil. A large incinerator can accept in the region of 100,000t/year.

Although incineration is a destructive technology, it does produce residual wastes in the form of ash and gaseous emissions. The latter have caused concern in the proximity of incineration plants handling toxic wastes, especially regarding the deposition of dioxins. The tightening of environmental legislation in Europe, and the improvement of pollution control technology in the industry, is leading to improvements in materials handling, de-ashing and the control of emissions to air, in both new and existing plant.

Various forms of incinerator plant exist, and these include:

- rotary kilns;
- plasma arc furnaces;
- fluidised bed incinerators;
- cement kilns;
- multiple hearth incinerators;
- circulating bed combustors.

The suitability of a contaminated waste to a particular type of incinerator should be approved by the operator. A variety of wastes from coal and steel facilities may be treated by thermal methods. Fluidised bed incineration for example, has been used to treat waste tar from coking plant operations, at a throughput of approximately 450 t/h.³⁶

Whilst incineration is often carried out at permanent facilities, mobile units are also available. Although these have the advantage of not requiring the transport of the wastes over large distances, in practice it may be difficult to obtain permission from a local authority and/or environmental regulation authority to operate such plant in some areas. Infrared and electric units are available as mobile incinerators.

11.7.3 Two-stage thermal treatment

Introduction

The two-stage thermal treatment of volatile contaminants can be achieved by systems that release the contaminants under heating and then thermally destroy them in the gaseous phase.

Rotary kiln incineration

Rotary kiln incineration is a commonly used thermal treatment system, which can also be adapted for two-stage treatment of contaminated materials at lower temperatures than other methods. The rotary kiln

consists of a long inclined tube, lined with refractory material, which is slowly rotated whilst the material within is heated, either through the shell of the vessel or via pipes within the kiln. The exhaust gases, containing volatile fractions of the material undergoing treatment (including water and contaminants), are collected and passed into a secondary chamber for thermal treatment of the gases and fine-grained particulate material.²¹⁰

Rotary kilns, which generally have a high throughput, are able to accept waste materials of varying consistency, including building wastes, although clays can form clods during treatment.¹²

Wet oxidation

Wet air oxidation is a decontamination treatment involving the exposure of oxidisable contaminants to gaseous oxygen, in the presence of water, at elevated temperatures. It can be used to treat soils and effluents contaminated with a variety of organic compounds, including coal tars.²²⁸ These contaminants are largely converted to soluble, non-toxic, biodegradable residues in the resulting condensate from the reactor vessel, and can subsequently be treated or disposed of.

Evaporation and condensation

Other two-stage thermal treatment systems also exist. One such system, developed in the USA, vaporises volatile contaminants into a gas stream, which is then condensed to produce a liquid for second stage treatment. This has been developed as a transportable plant.²³³

11.7.4 Vitrification

The vitrification process applies intense heat to contaminated solid wastes, which are pre-mixed with silica particles or other suitable materials *e.g.* sand, limestone, alumina, fly ash. The heat not only drives off volatile and combustible components but in addition causes compounds with

extremely high boiling points (including the silica) to melt and fuse on cooling, so forming a solid, glass-like end product as the residue from the process. The glass product can be produced as small particles (frit) or as cast blocks. This vitrified product is chemically inert, and of potential use as a construction material *e.g.* in coastal defences. Vitrification may therefore be seen as a waste recycling activity.

The option to vitrify waste is limited, as with most techniques, by the chemistry of the materials. Some wastes *e.g.* those that are highly alkaline, may not be suitable for processing.

Vitrification for the treatment of contaminated soils is a relatively infrequently used process, and the availability of equipment in Europe is somewhat limited. It has the potential to become more widely used, however, and may be of particular use for smaller volumes of highly toxic materials. Typically a vitrification plant may have the capacity to treat 300-500 tonnes of contaminated material per day.¹⁵⁹

11.7.5 Application and cost

Thermal treatment is a relatively expensive technique in relation to other waste disposal and treatment options. This is principally due to the high capital cost of the treatment plant and the large energy inputs needed to maintain the high temperatures required (in the range 800-2500°C). Thermal treatment of contaminated solid materials, such as soils containing a high proportion of inert inorganic matter, tends to be a relatively inefficient processes because heat must be transferred throughout the mass of the waste. Organic soils can be less expensive to incinerate due to the higher proportion of combustible material present, so that some of the heat required is produced by the waste material rather than the fuel.

The cost of incineration depends to a great extent upon the type of waste, as precautions during the processing and the subsequent treatment and disposal of residues will differ according to the original nature of the

contaminated materials. This means that the operator of the incinerator will require a detailed description of both the physical and chemical nature of the wastes prior to the quotation of prices and acceptance of the material.

As the cost of thermal treatment is high, and the process is largely destructive, such treatment is best limited to small volumes of highly contaminated materials. The advantage of such a disposal route is that once agreement has been reached with the operator all that is required is the safe removal and transport of the contaminated materials to the thermal treatment plant. This can be undertaken relatively quickly, thus removing the source of risk from the site during the reclamation. However, the location of the thermal treatment plant in relation to a given contaminated site may limit the sites to which this treatment technology can be applied.

Box 11.4 lists some further types of thermal treatment, which are currently receiving attention at field scale.

11.8 Non-destructive decontamination techniques

11.8.1 Introduction

There are a number of technologies for the treatment of contaminated materials which fall under the general classification of non-destructive decontamination techniques, as they do not completely destroy the soil. These can be subdivided into the following categories:

- solidification and stabilisation;
- biological;
- separation.

The principle of these techniques is to immobilise, degrade or separate the contaminant in the soil or water which they pollute. The nature of the

Box 11.4: Other thermal treatment systems

Amongst recently developed thermal treatment methods are:

- Thermal stripping of volatile contaminants;
- Radio frequency heating of soils to volatilise contaminants at temperatures of up to 600°C;
- Electric heating of soil *in situ*, using buried electrodes to volatilise contaminants;
- *In situ* vitrification, using graphite electrodes and massive electrical current;^{93, 94}
- Infrared incineration;
- Advanced electric reactor.

These technologies are either of limited availability or only on trial at pilot scale. They are available, as with most thermal treatment technology, through specialised contractors who should be consulted fully to ensure the suitability of the techniques to the waste in question. The technical details of some of these techniques have been summarised.¹²

contaminant(s) and the soil, and their interaction, are critical factors in determining the applicability of the technology. However, once the suitability of these techniques has been established for a particular site, they offer powerful tools for the reclamation process.

Decontamination processes may be applied either to excavated or extracted materials (*ex situ*), or within the relatively undisturbed soil-groundwater matrix (*in situ*). There are a number of advantages to the treatment of contaminated soil and groundwater without recourse to excavation of the materials:

- less chance of disturbance of the ground exacerbating pollution outside the contaminated area;
- the potential for undertaking treatment whilst a development proceeds at the site surface;
- cost and time savings by avoiding the excavation of materials;
- simultaneous control of pollution plumes during treatment.

Whether a given decontamination treatment is undertaken *in situ* or *ex situ* depends on:

- the limitations of the method;
- the ground conditions at the site where treatment is required;
- the type of contamination;
- relative costs of the available options.

11.8.2 Solidification and stabilisation

Introduction

In some environments chemical contaminants become naturally bound to indigenous soil particles in such a way as to render them immobile, and therefore less polluting. Clays, for instance, are important constituents of soil in this way, and without them many soil chemicals would be washed out of the soil by leaching.^{102, 229} This property of binding has been utilised to good effect in artificially created systems in order to form complexes between contaminant chemicals and a matrix of soil and other materials. The solidification and stabilisation of wastes have thus become important options for the treatment of toxic materials, limiting the solubility or mobility of the contaminants concerned.

In practice the process of solidification for hazardous wastes also involves stabilisation processes. Here, the two processes have been separated for the purposes of illustration.

Solidification

The fixing of contaminants within a resistant solid matrix is termed solidification. The end product, often termed a monolith, has a high degree of structural integrity. In cases where solidification occurs by the physical trapping of contaminants within the pore spaces of a solid, rather than by chemical fixation reactions, the process is known as

microencapsulation.¹⁸⁸ These processes may use concrete-based matrices or thermoplastics, such as asphaltic or polymeric compounds.

These methods are likely to include two principal stages:

- minimisation of contaminant solubility;
- cementation of the contaminant(s) by the use of a binder.

Unless contamination is already in a solid form *e.g.* dusts or metal particles, the initial stage of a solidification treatment may include the separation of the contaminant into a solid phase. In the case of organic contaminants this may include the use of clay minerals to form bonds with the contaminant molecules.

The binder materials are usually cementitious, and can include Portland cement, powdered slags, power station fly ash and kiln dust, in varying proportions. The contaminated materials are mixed with these dry binders, and are then hydrated to form of a slurry or paste. This mixture is then cured in appropriate moulds to form the solidified matrix.

The choice of stabilisation pretreatment and binder depends on the chemistry and structure of the contaminated soil, and is a matter for a specialist subcontractor. Their decision over the most appropriate treatment may rely on previous experiences with similar soils, or on laboratory tests which will be undertaken prior to full-scale treatment. Laboratory tests of this sort should provide details of the stabilisation of the solidified wastes, and on their resistance to physical degradation, chemical reaction and leaching.

Chemical stabilisation

Whilst solidification involves the physical stabilisation of contaminant molecules, other techniques chemically treat contaminated soil without recourse to solidification. These techniques have limited applications to soils containing specific types of contamination.

Likely chemical treatments include oxidising agents, which chemically alter susceptible molecules, producing lower solubility and less toxic oxidised products, or chemical structures within which the original contaminants are bound. Care must be taken with these treatments to ensure that chemical oxidation products conform to the criteria of low toxicity and solubility, and that they are not likely to return to their former chemical state, and so cause pollution in the future.

The use of ozone for the treatment of contaminated soil and water has been widely investigated in recent years, and has been used successfully to treat organic contaminants.¹⁶⁸ Ozone gas is a powerful oxidising agent which will readily destroy hydrocarbon contaminants. Methods have been developed whereby ozone can be pumped into a soil-groundwater system for the treatment of organic contamination. The success of these methods tends to be limited by:

- the nature of the pollutants;
- permeability of the soil;
- organic content of the indigenous soil.

The cost of ozone treatment can be relatively high due to the energy costs incurred in producing the electrical discharge in an ozone generator, and because of the non-specificity of the treatment. The latter means that, as with many oxidising agents, the oxidising activity of the treatment will be consumed not only by the organic contaminant, but also by other organic substances in the material undergoing treatment.

All chemical oxidation methods, which involve the handling of potentially hazardous oxidising agents, are likely to require specialised equipment with which to apply treatment.

11.8.3 Biological treatment

Introduction

The ability of certain groups of aerobic microorganisms to degrade complex organic compounds to simple molecules, such as water and carbon dioxide, has been used to good effect in the treatment of organic contamination at contaminated sites in Europe and North America. The tolerance of microorganisms to high concentrations of toxic organic compounds, and their subsequent detoxification of these chemicals, can be applied to the treatment of pollution both *in situ* and in excavated soil and abstracted groundwater.

The use of microorganisms for the treatment of sewage and waste waters is not a new concept, and the bioremediation of contaminated soil and groundwaters makes use of well-established principles established in this field. Biological treatment thus usually requires the following key parameters to be optimised:

- a microbial population with the ability to degrade the organic contaminants of concern;
- a nutrient supply to suit the nutritional requirements of the microorganisms;
- pH values near neutrality;
- a supply of oxygen;
- water;
- temperatures that will allow microbial and enzyme activity;
- absence of inhibitors of microbial growth.

Whilst these conditions may all be present in an uncontaminated surface soil, such as under tilled agricultural conditions, in a contaminated soil many of these factors may be limiting the potential for microbial growth and concurrent degradation of the wastes. The aim of biological treatment is to optimise these factors in order to stimulate biodegradation.

This process of optimisation will therefore include one or more of the following:

- addition of mineral nutrients to the system;
- aeration;
- implementation of a watering and/or drainage regime;
- inoculation of the system with an appropriate source of microorganisms;
- application of other amendments *e.g.* growth factors, co-metabolites, lime.

The range of organic chemicals amenable to treatment in this way is extensive, but is limited to those compounds which exhibit reasonable aqueous solubilities, as it is soluble organic compounds that tend to be more biologically available (see Box 11.5). Coal carbonisation by-product contamination in soils and groundwaters, including coal tar components, phenols, oils and BTEX, is sometimes amenable to bioremediation, and laboratory studies and full-scale schemes have illustrated the success of microbiological treatments.^{119, 252}

Factors affecting the practical application of biological treatment methods can be summarised as follows:²⁰

- chemistry of the contaminants and their biological availability;
- temperature and seasonal fluctuations;
- soil conditions for ground engineering and aeration of the system;
- residual concentrations of contaminants remaining after treatment *i.e.* very low concentrations may not be achievable;
- potential formation of soluble and toxic intermediates.

The limitations imposed by climate are most likely to include those of low temperature and extremes of rainfall. Thus, in temperate northern Europe ambient biological treatment will typically be limited to a period of 25-35 weeks, whereas in warmer Mediterranean climates the treatment season will be longer.

Box 11.5: Typical organic contaminants of coal and steel sites and their amenability to biological treatment

Readily treatable contaminants with some aqueous solubility e.g. 10^2 - 10^5 mg/l, include:

phenols, benzene, toluene, xylene, light mineral oils, petroleum hydrocarbons.

Contaminants of lower solubility e.g. 10^{-3} - 10^2 mg/l, treatable in some cases include:

tar oils, heavier mineral oils, more soluble fractions of coal tar (e.g. naphthalene, phenanthrene, acenaphthene).

Contaminants with negligible solubility ($<10^{-3}$), unlikely to be successfully treated by biological means include:

heavy fractions of coal tar (e.g. dibenzoanthracene), pitch, coal and coke, ferrocyanides.

In situ treatment

In situ biological treatment uses equipment to stimulate the biological degradation of contaminants present at depth in the soil. This equipment often consists of pipes, pumps, wells and dosing tanks, sometimes partly contained within small transportable units on site, which circulate groundwater through an area of contaminated ground, whilst applying amendments to the system to stimulate microbial degradation.²¹ The volumes of contaminated material below the surface may be confined within placed barrier walls, or in areas that are unconfined other than by the careful control of groundwater pumping. A typical scenario is illustrated in Figure 11.7.

A variety of chemical amendments may be applied to the circulating leachate and groundwater within *in situ* biological treatment systems.

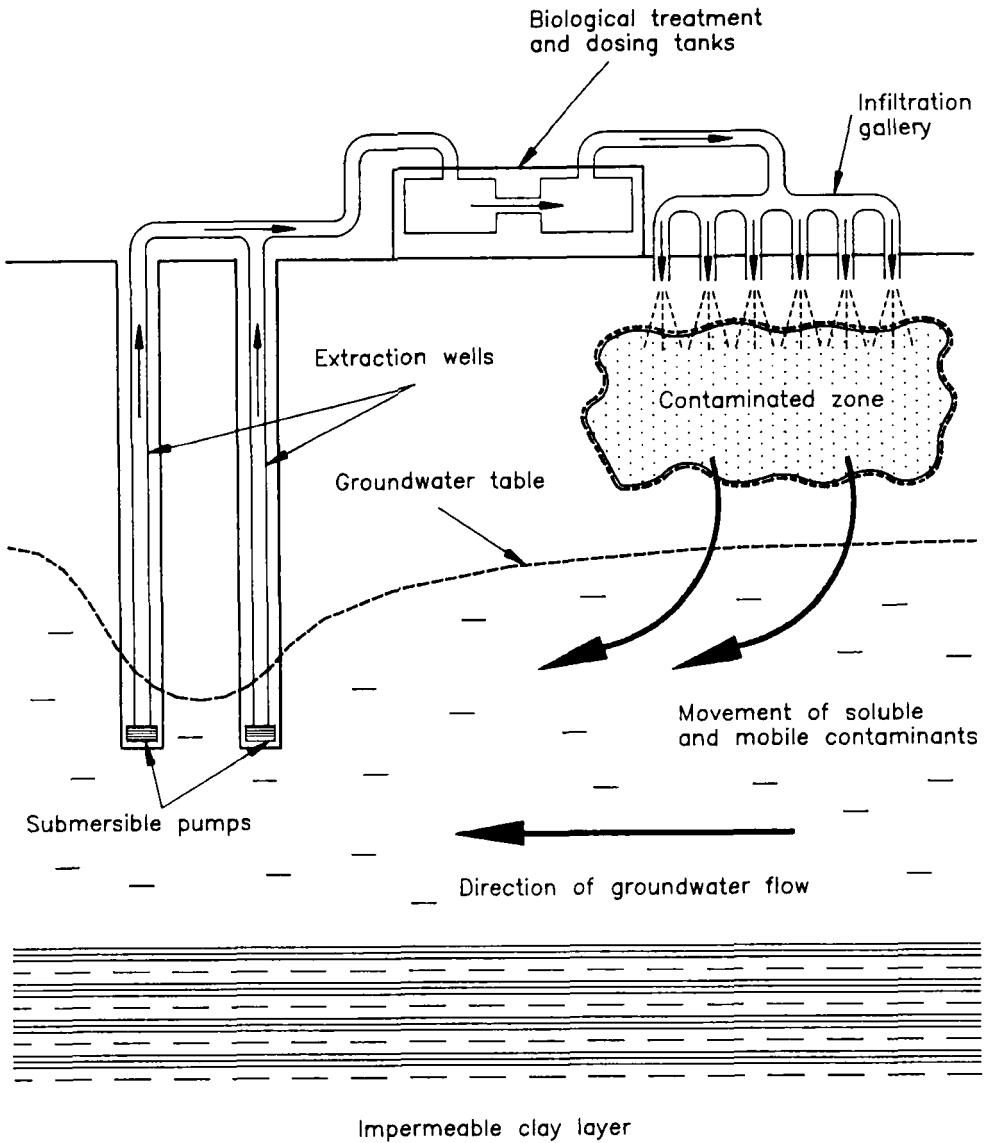


Figure 11.7: Example of a typical recirculating *in situ* biological treatment system

These include nutrient sources (*e.g.* proprietary blends, spent brewers yeast, molasses), solubility enhancers (*e.g.* surfactants) and sources of oxygen (*e.g.* air, hydrogen peroxide). Specific live cell preparations of bacteria are also added in some circumstances, and some such preparations are now available in dried, packaged form. The benefits of using such microbial inocula rather than relying on the stimulation of indigenous soil microorganisms are, however, often difficult to quantify.

There are a number of variations on the general theme of *in situ* treatment. Most rely on the extraction, recirculation and amendment of groundwater over the period of treatment, which may take from a few weeks to a few years depending on the situation. Whilst all schemes should pay due attention to the simultaneous treatment of both soil and groundwater in the saturated soil zone, problems may arise in the treatment of contamination in the vadose zone. In some cases this has been overcome by recirculating groundwater through this zone before it is returned to the groundwater, as illustrated in Figure 11.7. Alternatively, where volatile organic compounds are present, vacuum extraction or bioventing may be incorporated into the clean-up system (see Section 11.8.4).

Ex situ treatment

Where the ground conditions do not allow the *in situ* biological treatment of contamination *e.g.* where permeabilities are too low, it may be possible to excavate contaminated soil and treat it in above-ground, or *ex situ* soil heaps. These heaps are aerated either by conventional agricultural tillage, or by the incorporation of aeration pipework throughout the soil mass. In these cases volatile contaminants may be lost to the atmosphere by air stripping, and initially rapid declines in the concentrations of some contaminants may be observed. However, when compared with *in situ* systems the aeration status of an *ex situ* system tends to be more uniformly controlled and the application of nutrient and microbial amendments can be undertaken with conventional agricultural spraying equipment. To avoid the loss of leachate from the system, soil

treatment beds are often built on impermeable bases, incorporating a drainage system. This system may drain to a collection sump from where the leachate can be collected and treated or recycled. In some cases *e.g.* derelict industrial sites, it may be possible to construct soil heaps on areas of hardstanding, and use existing drainage runs to collect leachate. Where this is not feasible, durable plastic membranes and gravel drainage layers can be used in combination, as an impermeable, drained foundation to an *ex situ* treatment system.

In addition to chemical and microbial amendment of excavated soil systems, there is the opportunity to manipulate the physical nature of the soil to aid biodegradation. In this way materials can be added to aid the workability of clay *e.g.* lime, and to improve the structure of the soil to enhance aeration and drainage. The latter may be achieved by the application of uncontaminated organic matter or inert material such as gravel. In an extreme case, organic material may be added to contaminated materials with the intention of creating a composting system. Here, the quantity of organic material will tend to outweigh that of the contaminated soil, and moisture levels (approximately 40%) tend to be higher than for soil treatment heaps (approximately 10-20%), such that the conditions are created for intense aerobic microbial activity which initially produces a rise in temperature within the heap. Suitable organic media for composting include sewage sludge, green wastes, manure, wood chips, bark and straw, and to some extent the use of a composting system to decontaminate soil materials will be limited by the local availability of these organic substrates.

Composting is a complex and dynamic process which relies on a succession of microbial populations during the decomposition of organic materials. Under controlled conditions it can result in the formation of a beneficial medium for soil conditioning. This can be of benefit to the establishment of vegetation during a reclamation scheme (see Section 14.4).

Composting has not yet been widely used for the treatment of contaminated soils, but it is likely to find more applications in the future.

11.8.4 Separation

Introduction

Various techniques are available for the separation of contaminants from soil particles; as treatments for contaminants within the ground and for excavated or extracted contaminants.

Vacuum extraction

Vacuum extraction is a physical technique for the removal of volatile organic compounds from soil and groundwater. It may also be referred to as vapour extraction or soil venting.

Vacuum extraction is an *in situ* treatment, and relies upon the extraction of volatile contaminants from wells within a contaminated area, by the use of vacuum pumps or fans. The application of suction to the wells causes air in the surrounding soil to flow into the well, along the pressure gradient, and out through the extraction system. This air will contain contaminants present in the vapour phase. The decrease in pressure within the soil air will also increase the volatilisation of organic compounds *i.e.* contaminants, and thus aid their removal from the soil. Depending on the nature of the contaminants and their concentrations in the extracted air stream, an emission control system may be used to clean the air prior to discharge to atmosphere. Such control may use condensation, adsorption, biological or thermal treatment.⁴⁴

The application of vacuum extraction is limited mainly by two main factors:

- soil permeability;
- contaminant volatility.

Usually the extraction system is based on a series of wells, the depth and spacing of which is critical to the success of the system. The extraction system configuration is based on an understanding of the contamination profiles and the permeabilities of the soil.¹⁵⁴

A schematic diagram of a typical system is shown in Figure 11.8.

It is more usual for contamination by volatile and semi-volatile compounds to occur in both the vadose zone and the saturated zone beneath. In this case a dual vacuum extraction system is used. In dual vacuum extraction water is removed from at or just below the groundwater table in the extraction wells, either by application of a vacuum or by a submersible pump. Contaminants in the groundwater are removed with the groundwater, and those which remain in the soil, adhering to soil particles as the groundwater table is lowered, are removed by the vacuum applied to the unsaturated zone (see Section 12.5.3). As organic contaminants tend to be most concentrated at the interface between the groundwater table and the unsaturated zone above, dual vacuum extraction is frequently the most effective treatment method. However, the extracted groundwater will generally require treatment to separate and degrade contaminants (see Section 12.5.3).

The flow of air through the soil induced by vacuum extraction also enhances biological degradation of contaminants. This biological activity can be encouraged by application of soil amendments to the unsaturated zone.¹⁶³

Soil vacuum extraction systems tend to be suited to contamination such as that caused by spillages of organic liquids. The technology has been used successfully to remove light petroleum and chlorinated hydrocarbons, and is of some use where volatile coal carbonisation products contaminate the deeper strata in permeable soils.

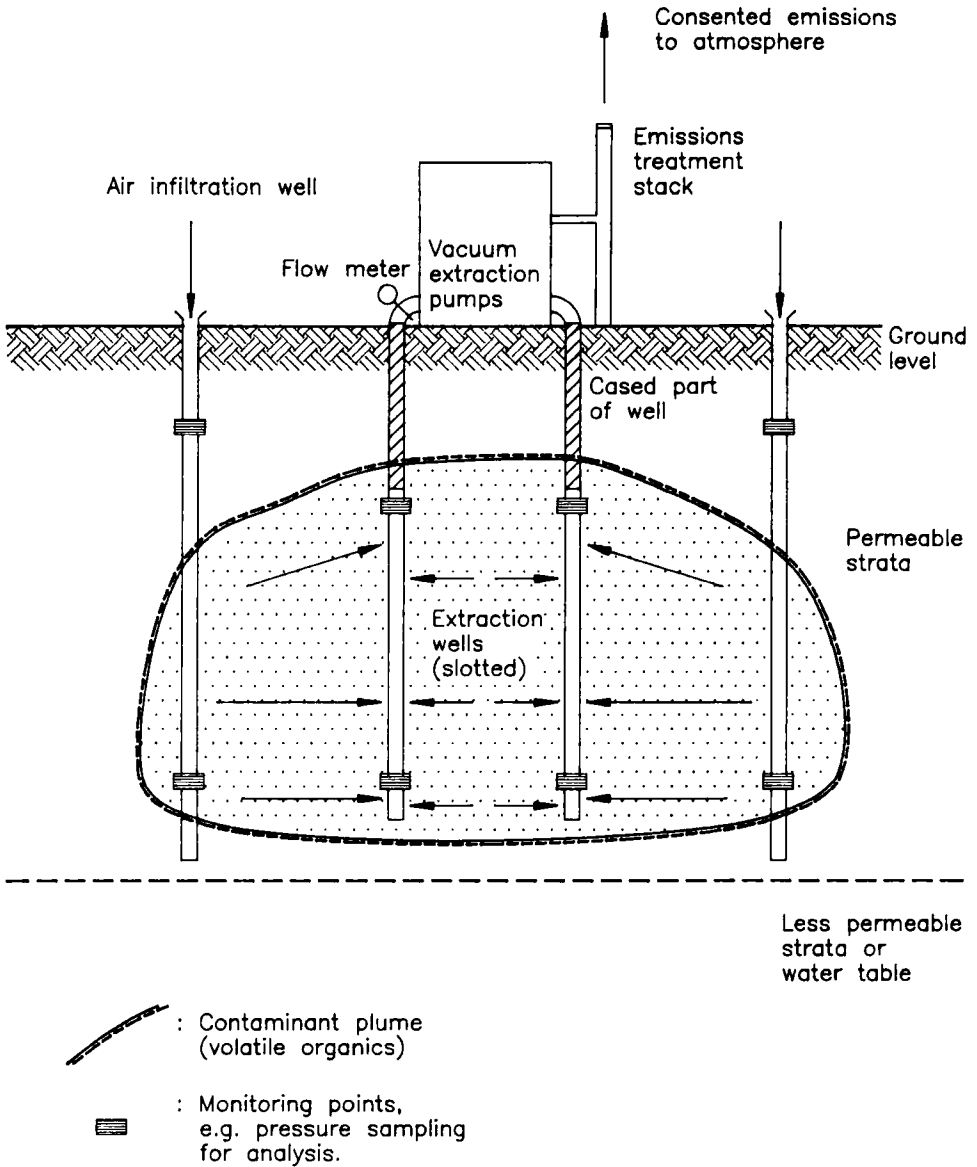


Figure 11.8: Schematic diagram of a vacuum extraction system for volatile organics remediation in soil

Soil washing

Soil washing is a general term applied to a number of water-based processes for the separation of contaminated materials from soils. It is applicable to a wide range of contaminants, from metals to volatile organics, and can achieve efficient decontamination in suitable soils.

The processes generally depend on the observations that either contaminant molecules are water-soluble, or that they are commonly associated with the fines fraction of soils (notably clay and silt minerals, hydrous oxides and organic matter). These contaminated fines can be separated from the soil matrix by various aqueous systems that rely on particle separation, so leaving behind a largely uncontaminated 'soil' residue, which can be replaced on site or reused elsewhere.

A typical process flow diagram for a soil washing facility is shown in Figure 11.9.

The residual contamination arising from a soil washing process can be placed into one or more of the following classes:

- contaminated wastewaters, which then require further treatment to remove contaminants from solution;
- contaminated fines, often separated as sludges, which then require disposal;
- emissions to air, in the case of volatile compounds.

Soil washing is a European technology, developed during the 1980s in the Netherlands and Germany,¹⁷⁸ using well established principles of particle size separation used in the minerals industry. Several operators throughout Europe have this technology at their disposal, and some of the smaller throughput plant is transportable,⁹ allowing it to be taken to a site, and avoiding the need to transport toxic materials over long distances. Such equipment, however, requires sources of power and

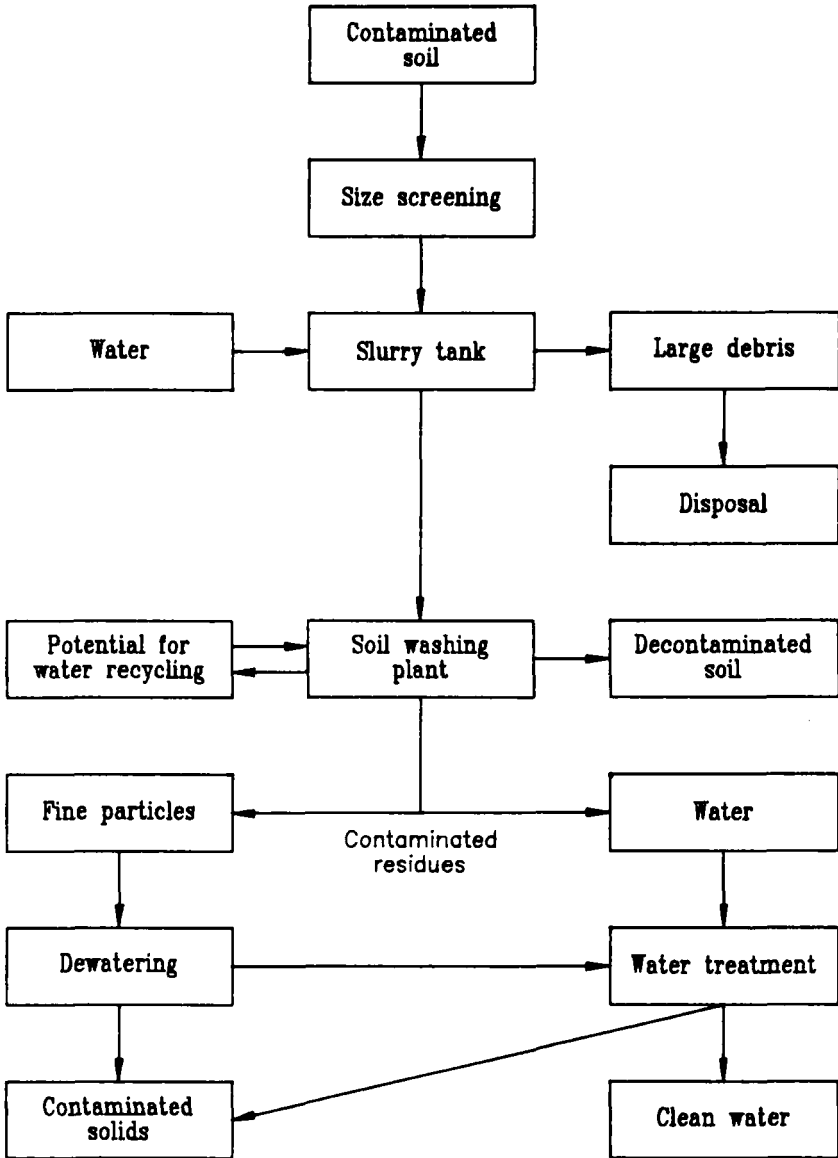


Figure 11.9: Flow chart for principal processes and products of a typical soil washing decontamination treatment

water, as well as on-site space; possibly 1.5ha for a 20t/h soil washing plant.²⁴⁴

Generally, soil washing is particularly suited to sandy and gravelly soils, where significant reductions in the volume of contaminated materials can be achieved. In this way soil washing may be able to provide a one step treatment, or may be useful as a pretreatment, prior to, for example, the incineration of contaminated fines material.^{208, 244}

Silt and clay soils are less amenable to treatment, and contaminants that are particularly hydrophobic are more difficult to remove. The latter may be overcome to some degree by the use of solvents or surface active compounds (detergents), although these may interfere with the efficiency of washwater treatment.

Variations of soil washing include adaptations of mineral ore processing techniques,¹⁸⁴ high pressure jet grouting technology,¹⁰⁶ and hydrocyclones.

Solvent extraction

Solvent extraction is similar in principle to soil washing, in that contaminants are removed from the soil matrix into a liquid medium. In this case however, the liquid medium is not water, but an organic solvent. Such solvents include non-chlorinated organic solvents *e.g.* triethylamine, carrier oils, and liquified gases *e.g.* propane and/or butane (critical fluid extraction¹³²).

The technology is generally applied to the treatment of organic contaminants such as PCBs, volatile organics and petroleum hydrocarbons, and is of less use for the extraction of metals and inorganics. Solvent extraction has shown potential for the treatment of coal tar wastes in soil.

Because of the potentially hazardous nature of solvents used in the extraction process, and the cost of these solvents, solvent extraction

treatment plants have the facility to recycle the solvent. Thus the process consists of a soil-solvent contactor vessel, where the soil is washed in the solvent, followed by a solvent recovery facility where the solvent and the contaminants are separated, and the solvent recycled. Separation of solvent and contaminants can be carried out by steam stripping.¹¹¹ The process therefore results in the production of concentrated contaminated residues, which require disposal or further treatment.

Generally solvent extraction facilities are transportable, although rates of throughput tend to be low, and the availability of such equipment in Europe is limited.

Leaching, pumping and treating

The leaching of contaminants from soil, and the pumping of contaminated groundwater and subsequent treatment above ground are variations on the themes of soil washing/solvent extraction and *in situ* treatment respectively. Section 12.5.3 considers pump and treat methods for contaminated groundwater.

The types of treatment which can be applied to contaminated groundwater in surface treatment facilities may include some of those discussed earlier, such as air stripping, biological treatment and adsorption, as well as less established techniques such as the biosorption of metals.¹⁹

The application of leaching methods to the extraction of contaminants from soils is an emerging technology that has potential for the controlled release of contaminants, including metals, from polluted soils.

11.8.5 Application and integration of techniques

On most former industrial sites, and especially those of former coal carbonisation or steel making activities, it is rare that a single treatment

technique will meet all the requirements of site clean-up. This is often due to constraints posed by the presence of either:

- complex combinations of contaminants;
- discrete areas of different types of contaminant;
- variations in ground conditions;
- areas required for different end-uses, and so different clean-up standards.

As a consequence, a combination of techniques can provide the most effective solution to site decontamination. On-site decontamination is frequently combined with off-site disposal or physical containment of areas of low treatment potential. For example, in the decontamination of a gasworks site in the UK, *ex situ* biological treatment was used to treat phenolic and coal tar residues, a clay-lined containment cell was constructed on site, and other materials were disposed of to a licensed landfill.³¹ Alternative scenarios may use two or three stage treatment to achieve decontamination objectives, and some of these are highlighted in Box 11.6.

The choice of treatment(s) therefore needs careful consideration following site assessment and feasibility studies, and combinations of different techniques can be more reliable than single treatments where contamination at a site involves heterogeneous contaminants and ground conditions.

The application of remedial treatment or a combination of treatments must always take into account the sensitivity of local communities to the on site works. Every effort should be made to avoid inconvenience to local residents during site decontamination by minimising such effects as noise, dust, odours and traffic congestion.²⁴⁹

Box 11.6: Some examples of combined treatments used to obtain required standards of decontamination

- *In situ* treatment of volatile contamination by vacuum extraction, and biological treatment of abstracted groundwater.
- Soil washing of organic contaminants followed by the biological treatment of the contaminated fines in an *ex situ* system.
- Treatment of pumped groundwater in an above-ground biological reactor, which subsequently requires polishing to attain required low levels of contaminants, using an activated carbon filter.
- Physical containment of contaminated ground prior to *in situ* bioremediation.

11.9 Standards and objectives for decontamination

11.9.1 Considerations

Whilst the choice of the most appropriate method of decontamination is important, it is also important to adopt appropriate chemical standards for the end result of a decontamination operation. These considerations will be affected by:

- lack of established standards for soil clean-up on a national or regional basis;
- incomplete understanding of the objectives of clean-up in terms of risk reduction;
- incomplete understanding of the exact nature of the contamination present;
- high variability in the distribution of contamination through the soil, both before and after treatment.

Despite the importance of setting decontamination criteria, this has in some instances been undertaken on a piecemeal basis, and has led to problems after the application of the treatment, for example where standards of decontamination have not been agreed by a controlling

authority. In some areas of Europe there exist regional or national standards for soil contamination, such as in the United Kingdom,¹²¹ the Netherlands,¹⁶⁵ and various regions of Germany (see Section 2.6.5). These standards form guidance for the practitioner and are advantageous because:

- the target concentrations can be easily defined;
- the choice of remedial treatment will be limited to those methods which are able to achieve the required final concentrations;
- the liability of the site owner or treatment company for future pollution arising from the site is limited providing that the defined standards are met during clean-up.

Where no guidance levels are defined then it is the responsibility of those concerned with the redevelopment of a contaminated site to agree on suitable criteria for decontamination, in liaison with the statutory authorities. Thus, regulation by negotiation aims to bring together all the parties concerned, including the regulator, to gain an agreement on targets for reclamation.²⁵⁴ Agreement should be made on the basis of:

- the intended long-term use of the site after reclamation;
- the removal of risk associated with the contamination, its effect on health and safety at the site, and the proposed after-use;
- the adequate protection of groundwater in the area, and the environment in general.

Agreement and ratification of target levels between the parties concerned can be a long process, and should therefore start at an early stage. Informed parties should take into account the environmental availability of the soil contaminants in relation to local conditions, and also the background levels of contamination in the region.⁹⁵

Once target concentrations have been set, and a method of remediation chosen, the next stage is to choose the best way to monitor the treatment. Design of a monitoring strategy requires consideration of the following:

- chemical analytical methods to be used;
- sampling regime during the treatment operation;
- strategies to monitor the site after treatment is complete.

11.9.2 Analytical methods

Introduction

The choice of analytical method for the accurate assessment of a specific contaminant concentration is fundamental to the treatment programme. Analysis of samples collected during a site investigation is discussed in Section 2.6.4. For many chemical parameters there are a number of alternative analytical methods available. The following should be taken into consideration when choosing which methods to use:

- a nationally or internationally accepted standard method is generally preferred;
- throughout treatment, monitoring and validation, a single method for a single chemical parameter should be adhered to;
- analysis should be carried out by a recognised analytical laboratory, preferably one that is nationally accredited by a controlling body, and which adheres to strict quality assurance procedures.

Detection limits

With particularly toxic chemicals the concentrations required to ensure adequate risk reduction may be very low; in the region of a few parts per million for soils, or a few parts per trillion for groundwaters. The detection limit of the method chosen must be below the concentrations required after treatment of the contaminated material.

The accurate detection of low concentrations of pollutants is thus an important issue which should be noted at the outset. Mistakes have occurred in some cases where the detection limits of a standard method were too high to allow the adequate determination of concentrations after treatment.

Leaching tests

The importance of the environmental availability of a contaminant should not be underestimated in assessing risk. The solubility and mobility of a contaminant is likely to affect:

- biological availability;
- pollution potential;
- toxicity.

Leaching tests aim to subject a sample of contaminated material to a set of conditions that simulate the rigours of environmental liquid-solid contact, and the chemical and physical changes that this causes. The aims of a leaching test are to extract the available (or potentially available) contamination from a sample into the liquid phase.²⁴⁶

The use of agreed leaching tests to accompany standard quantitative procedures for soils can enhance the monitoring and validation of a clean-up scheme, and may offer valuable supplementary data to accompany that of soil chemical concentrations.

Leaching tests are discussed further in Section 12.4.5.

11.9.3 Sampling regime

Introduction

The determination of a sampling pattern for the investigation of contamination at a site is discussed in Section 2.6.2. Similarly, a

sampling regime must be agreed for the monitoring and validation of a decontamination operation, even where contaminated materials are to be moved off site. The choice and consistency of sampling pattern is important if meaningful data are required on the clean-up operations.

On-site treatment

Where soils and groundwater are to be treated on the site it is important to undertake sampling and analysis to establish the concentration of contaminant(s):

- prior to the treatment;
- during the treatment;
- at the end of the treatment.

Where statistically meaningful data is required *e.g.* for regulatory compliance, the operator must ensure that the number of samples taken is consistent throughout the treatment, and that enough samples are taken to allow for the variability between results on a single sampling occasion.

Off-site disposal

Where contaminated materials are to be carried off site there also needs to be a suitable sampling regime in place. This should address the contamination status of:

- the materials moving off site;
- materials left on site;
- imported fill materials.

An agreement with a waste transport contractor, or fill materials supplier, concerning a sampling strategy for loads of soil materials moving on and off site should be made at the outset of the reclamation works. This should ensure that only materials of a suitable chemical quality are treated, disposed of, or used during the scheme.

11.9.4 Monitoring

Monitoring of a treatment process is necessary in order to maintain the level of treatment required and to detect any under-performance of the process. In addition long-term monitoring of a site may be required to detect any failures of a treatment at some point in the future. The latter is particularly important where wastes have been retained on site by methods such as containment, solidification or stabilisation.

Monitoring systems commonly relate to gas production *e.g.* from landfills, and to groundwater quality. Both can be successfully monitored by sampling from borehole stand pipes, installed and maintained to a suitable standard on or adjacent to the treated area.

11.9.5 Validation

At the end of a contaminated land treatment programme it is most important to assess the success of the scheme, in terms of contamination decline, and final decontamination levels. This may be particularly so when validating the success of an on-site decontamination treatment that has involved the separation or degradation of pollutants in the soil *e.g.* biological methods.

The validation is likely to conform to the requirements of a regulator, who may stipulate:

- the target concentrations;
- the methods to be used in analysing the contamination levels;
- the minimum number of samples that have to be taken from a given site area;
- a proportion of samples which are required to fall below the target concentration at the end of the treatment.

In the event of a treatment failure, the regulatory body may also require assurance of an alternative treatment or disposal route for materials that remain contaminated.

11.9.6 Costs

The cost of any decontamination scheme should allow for the costs of an appropriate sampling and evaluation programme, according to the factors discussed in Sections 11.9.1 to 11.9.5. In some cases the cost of such a programme may form a significant part of the total cost of the scheme. Any treatment for contaminants which are expensive to analyse accurately *e.g.* dioxins, may incur substantial analytical costs.

It is therefore important to accurately assess the requirements of sampling and analysis at all stages of a decontamination operation, and the costs that accompany these actions. The costs are likely to include:

- time for personnel to carry out sampling;
- allowances for the establishment of monitoring access points and equipment *e.g.* boreholes, piezometers, on-line and automated measurement devices;
- analysis of samples;
- documentation and reporting of results.