APPROPRIATE GEOTECHNOLOGY FOR HONG KONG'S LANDFILL LINERS

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SYNOPSIS

Plans to place unusually large depths of waste in steep sided valley landfills, and also on near-shore marine landfills, have led to the need to carefully evaluate the appropriate geotechnology for forming leachate containment systems for Hong Kong's landfills. A number of different systems have been considered. Whilst carrying out design work on these various systems, careful attention has been paid to relevant design guides and standards from other parts of the world; mainly North America and Europe. Since some conditions in Hong Kong differ from these other countries, it has not been possible to simply copy their design methods. This paper reviews the various liner systems that have been considered for the conditions specific to Hong Kong's landfills.

INTRODUCTION

Hong Kong's landfills are either in steep sided valleys (with natural slopes often between 25° and 40°) or are marine landfills placed on areas of reclamation along the mountainous coastline. Some of the newer landfills encompass a combination of both valley and marine areas. Many of the landfills operate co-disposal, in which hazardous waste is placed within the municipal waste. Depths of waste have increased rapidly from 30 m to 80 m, and now depths of 120 m to 140 m are planned. The underlying ground varies from strong rocks to soft marine muds. This has led to liner design becoming a very interesting engineering challenge.

With the rapidly increasing depths of waste, the need to provide improved leachate containment for these landfills was recognised in the mid-1980s. At that time, the most advanced and the greatest number of liner designs were to be found in North America, and attention was focused on learning from their experiences. In the U.S.A., liner design for hazardous waste landfills had already progressed, in some instances, to the use of triple liners (ie. three individual containment layers). The use of plastic, or geomembrane, liners for at least one containment layer had become mandatory in 1982. In Canada the emphasis was still on the use of single clay liners (Milligan, 1983). Within Europe, at that time, landfill liners were used in Germany, and to a lesser extent in the Netherlands and Denmark. Landfill liners were also used in Japan, though with their high density of population and shortage of land, the emphasis of landfill design has been on waste decomposition rather than waste storage. Thus, it seems the liner and drainage system in Japan has been provided more to control pollution, than as a containment system for waste storage as in the U.S.A. (Hanashima et al, 1989).

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There are differences and similarities between Hong Kong and these other parts of the world, and this paper reviews the various liner systems that have been considered for the conditions specific to Hong Kong's landfills. These alternatives have included geomembranes, clay, bentonite, concrete, asphaltic concrete and shotcrete; and combinations of these alternatives. The drainage layer alternatives of natural granular material and geodrains have also been considered.

HONG KONG CONDITIONS

Hong Kong has a mountainous terrain, with many steep sided valleys and inlets of the sea. The valley sides are mainly composed of strong igneous rocks that have weathered insitu to form an overlying soil that has the consistency of a weak rock. Deposits of colluvium from the parent material frequently overlie the weathered rock. Immediately offshore, this material is generally overlain by alluvium, covered with a layer of soft marine deposits. Thus the material underlying the proposed liner systems varies greatly in strength, compressibility and permeability.

Hong Kong lies just within the tropics, and has a warm sub-tropical climate with an average annual rainfall of 2.2 m. There are two distinct seasons of the year, of approximately equal length. The wet season is hot and humid with very high rainfall. The dry season is warm and dry with almost no rainfall. The very high summer rainfalls, up to 600 mm in one day, can lead to potential construction problems for some types of liner material; especially on the steep valley slopes. The high average annual temperature of 23°C leads to fast rates of decomposition of the refuse, which generates high temperatures which need to be considered for liner design and durability.

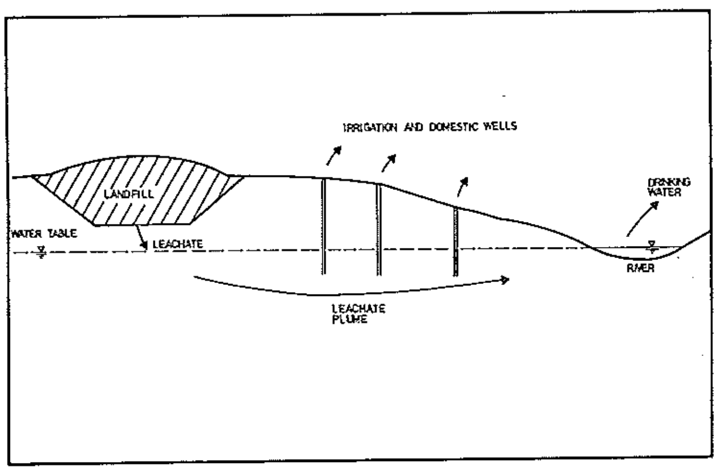

Fig. 1 Typical North American Situation Requiring Leachate Containment

In comparison, most landfills in the U.S.A. are located on relatively flat (slope angles up to 10°) land composed of sedimentary soils. Although the permeability of these sedimentary soils varies widely, their strength and compressibility does not vary as widely as the change from fresh igneous rock to soft marine muds. In the eastern two thirds of the U.S.A., landfills have often been placed in old borrow pits with side slopes (usually about 20°) on all four sides, forming a basin. For the newer landfills, construction has often been started with the excavation of basins for individual cells within the landfill. With water supplies often being obtained from the underlying groundwater table, the emphasis has been to contain the leachate within these basins, in order to stop it from travelling downwards and polluting the groundwater resource (Fig.1). Steep valley landfills, where contained leachate will flow down to the open mouth of the valley, and the occasional marine landfill, are only to be found in the western third of the U.S.A., where the climate is mainly arid.

Liner Performance Criteria

The consequence of liner leakage differs widely at the various locations of the landfills in Hong Kong. Groundwater is not commonly used as a resource for either drinking or irrigation water. Drinking water is obtained from surface reservoirs, which are in well guarded water catchment zones. Most of the landfills (with one notable exception) are located well away from the few farming districts where groundwater is used for irrigation. However, the sea is widely used for mariculture. Fishing junks can often be seen using their nets just offshore, and floating fish farms are very common within the many sea inlets. One landfill is located next to an extensive area of farmed oyster beds. Hence, the consequence of liner leakage for most of the valley landfills is relatively low, compared with other parts of the world where groundwater is used as a resource, whilst the consequence of liner leakage for the marine landfills is high.

The current minimum liner performance criterion is a coefficient of hydraulic conductivity of 10^{-9} m/sec, for a one metre head of leachate. At the landfill where groundwater is used for irrigation downstream, a coefficient of hydraulic conductivity of 10^{-11} m/sec has been selected. In addition, a minimum material specification of a single composite liner (a liner composed of two different types of material in contact with one another) has been selected. It is worth noting that for these low values of hydraulic conductivity the transmission process may involve diffusion as well as permeation (Quigley et al, 1987).

At present, the effectiveness of a leachate containment system in Hong Kong is assessed by monitoring offsite migration. That is, monitoring wells are placed along the site boundary in order to detect leakage from the site, and tests are conducted on samples of the organisms living adjacent to the site. If the containment system is found to be unsatisfactory, then barriers to leachate migration are to be installed along the site boundary.

Depth of Refuse

The enormous depths of waste being planned for the new landfills will exert very high stresses on the underlying liner systems. From weighbridge measurements of waste intake, and measurements of the volume of the void space filled, it is known that the waste is currently being compacted to a density of at least 1.1 Mg/m^2. With 120 to 140 m of waste, this could result in a stress of 1.5 MPa being exerted on the liner and drainage system.

Temperature

Little is yet known of leachate temperatures within Hong Kong's landfills. Measured gas temperatures have varied from 45°C. to 57°C., within the refuse. It is expected that the temperature near the liner, which is located close to natural ground at ambient temperatures, would be lower.

Howells and Pang (1989) reviewed the data on Hong Kong ground temperatures for the design of geogrids, which showed that at a depth of 3 m below the ground surface the annual mean soil temperature is 25°C., with a monthly mean of 28°C. throughout the summer months. Bearing in mind these high gas and ground temperatures, a prudent design temperature of 40°C. has been thought necessary for some liner systems; and a programme of field measurement has been initiated.

These temperatures compare with recorded leachate temperatures of 45°C. in landfills in southern Australia, and up to 75°C. in Austria (Lechner & Lahner, 1991). It should be noted that these temperatures are higher than those normally used for the design of geosynthetics in North America.

VALLEY LANDFILLS

There are various design considerations for a liner system for a valley landfill. Hong Kong's valleys are typically V-shaped, with 25-40° side slopes rising from near sea-level to a height of a few hundred metres. These steep and high side-slopes require the design of the side-slope liner to be considered separately from the liner on the flatter valley bottom. The underlying rocks, and weathered rocks, generally provide a firm base to the liner system; although there could be a small amount of differential settlement around the often sharp interfaces between fresh rock and weathered rock, and slope stability obviously needs to be considered. Where colluvium is present, it has less strength than the weathered rock, but it is still a relatively firm sub-base.

A combination of surface water flows and groundwater springs, many of which are ephemeral with the wet and dry seasons, require the inclusion of groundwater drainage under the liner. Flow of groundwater within the rock mass is mainly along faults, joints and relict joints. Many of the dykes have weathered to a clayey consistency, and these often form hydraulic barriers.

Unlike the basin landfills of the central and eastern parts of the U.S.A., where the aim of the lining system is to contain the leachate within the basin, the aim of a lining and drainage system in Hong Kong's steep valley landfills is to husband the flow of leachate down to the open valley mouth, where it can be effectively dealt with. It is unlikely, unless the drainage system is not functioning properly, that the leachate will build up to any great depth over the side-slope liner.

There could be many advantages to making the side-slopes even steeper. Excavation for steeper slopes would result in an increased void space for waste, and the provision of much needed material for other purposes, such as daily cover. The landfills require many millions of tonnes of fill material to be imported onto the site. Initial quarrying of the site could reduce these quantities. A profile showing the maximum amount that could be quarried is shown in Fig. 2. The resulting near vertical side-slopes could be used to advantage in the design of the liner and leachate drainage system. Any leachate travelling towards the valley sides would meet a near vertical leachate drainage layer, and would show a distinct preference to travel down this leachate drain rather than to pass through the liner. As a result, the demands placed on the side-slope liner would be decreased. The design of a near vertical liner is discussed in further detail later. This concept could also be utilised if any of the existing quarries in Hong Kong are to be used for waste disposal.

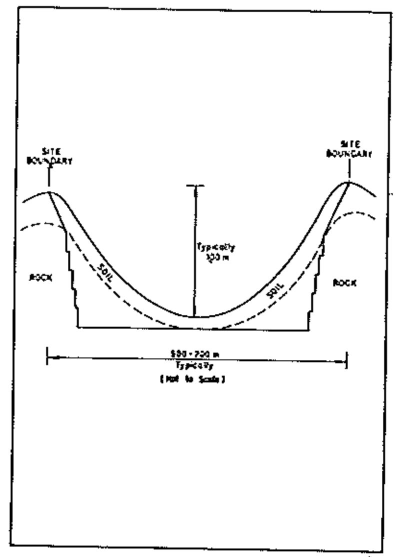

Fig. 2 Valley Landfill Cross-Section Showing Maximum Quarrying Potential

Except for having to allow for the large vertical stresses, the design of the liner and drainage system for the flatter valley bottoms is perhaps more conventional. Care is required even here, however, to ensure that the liner does not provide a slip surface which could induce a mass movement of the waste downslope. Mitchell et al (1990) record the failure of a landfill on a 1:50 (1°) slope in California. With depths of 120 m to 140 m of waste, at a density of over 1.1 Mg/m^3, the liner and drainage system on both the valley bottom and the lower portion of the side-slopes could be subjected to a vertical stress of 1.5 MPa.

MARINE LANDFILLS

The design considerations for the marine landfills are quite different to those for the valley landfills. Soft marine deposits, mainly muds with sand lenses, overlie alluvial deposits consisting of soft to firm clays containing gravelly sand lenses or layers. Because of their low permeability, these soils are viewed as a useful barrier to leachate flow. However, their low strengths give the designer considerable problems in maintaining stability, and their variable compressibility gives rise to considerable differential settlement problems.

The design of liners for the marine landfills is still in the development stage. One (the hydrogeologically preferred) design concept is shown in Fig. 3. Here the liner is to be placed below sea-level, so that any leakage of the liner will result in sea-water leaking into the landfill rather than leachate leaking out. The disadvantage of this concept is that it requires the construction of a water-tight sea-wall, in order to build the liner, and the provision of a substantial pumping system above the liner to cater for the drainage of possible sea-water leaks.

An alternative is to place the liner onto an area of reclamation, see Fig. 4. This liner could be made to slope back towards the land, thereby preventing the leachate from flowing towards the sea and its mariculture. The disadvantage of this concept is in the difficulty of providing an area of reclamation that is firm enough to provide

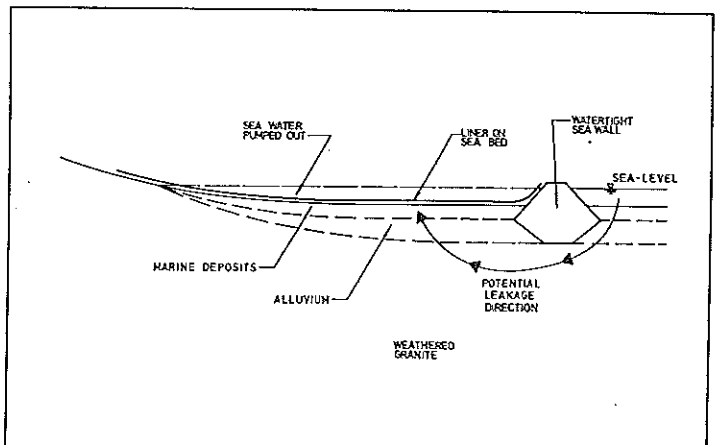

Fig. 3 Preferred Hydrogeological Concept for Marine Landfill

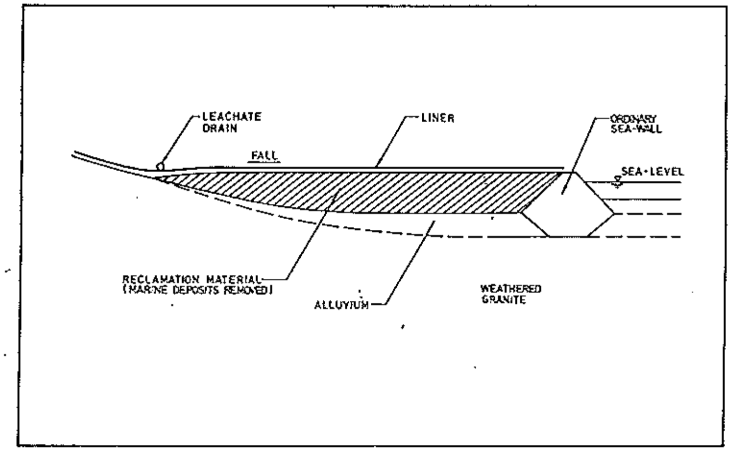

Fig. 4 Marine Landfill with Liner on Reclamation

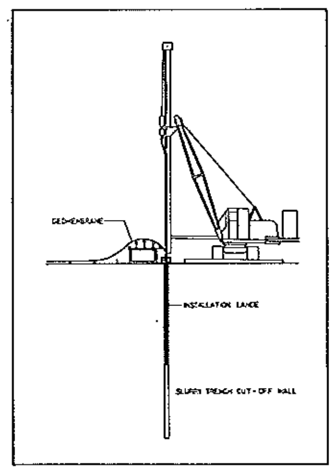

Fig. 5 Slurry Trench Cut-Off Wall with Geomembrane Insert

a good sub-base to the liner, with its large overlying depth and weight of waste. Most reclaimed land suffers settlement in the first few years of its life, from its own weight alone, and it is planned to place up to 100 m of waste within the marine portions of the new landfills.

In order to reduce the potential settlement, and more importantly differential settlement, beneath these horizontal liners to tolerable amounts, it has been found necessary to remove the soft marine deposits from the sea-bed. Even then, the underlying variable alluvium will result in large settlements, and differential settlements, occurring as a result of over 1MPa of stress to be induced by the overlying waste. The provision of a strong reclamation material is required in order that the liner will survive these differential settlements intact. This reclamation material may need to be reinforced, perhaps even with reinforced concrete.

A further alternative is to form a vertical barrier to leachate flow, such as a slurry trench cut-off wall. Low permeability slurry trenches are commonly used in remedial measures to old landfills in the U.S.A. (McCaudless & Bodocsi, 1987). In Germany, and the Netherlands, this concept has been improved by inserting geomembrane liners into the slurry trench (Fig. 5). A vertical barrier of this nature has already been used in Hong Kong for the containment of a power station coal ash lagoon adjacent to oyster beds (Wigmore & Kubrycht, 1989).

LINER MATERIALS

Six different materials have been considered in the design work for Hong Kong's landfills. These are geomembranes, clay, bentonite, concrete, asphaltic concrete and shotcrete.

Geomembranes

Geomembranes are very low permeability synthetic membranes, usually made from polymers. In the U.S.A. they are also called flexible membrane liners (FML). If they are properly installed on site, with a firm base, their coefficient of hydraulic conductivity to a one metre head of leachate may be as low as 10^{-12} m/sec. However, they are relatively weak materials, and can easily be damaged by stretching or puncturing. Their use under the stresses imposed by more than about 50 m of waste needs consideration of a composite liner (a single liner comprising two layers of different materials in contact with each other), with the other half of the composite providing the necessary strength and its own degree of impermeability.

Geomembranes need to be installed on smooth firm surfaces, and protected from puncture. Geotextile buffers are often used for puncture protection. On steep slopes, anchorages are required at regular intervals, in order that the tension and creep induced in the thin plastic sheets can be kept to manageable proportions. On very steep slopes, the installer has the problem of positioning people for seaming of the sheets, and testing of those seams. Attention to detail is required during design to ensure that the use of geomembranes (which have low coefficients of friction) on slopes does not introduce potential sliding surfaces, which would cause instability of the overlying waste (Mitchell et al, 1990).

Recorded friction angles of geomembranes vary widely from 5° to over 30° (Brendel et al, 1987), depending on the type of geomembrane and the material they are interfacing with. In order to improve these friction angles, manufacturers are producing geomembranes with textured surfaces. This texturing is being provided in a number of different ways, including spraying, brushing, and physical and

chemical indentation. These different texturing methods produce varying improvements to friction angles, and in the case of indentation can even change the basic strength properties of the material. With the very high stresses produced by large depths of waste, this surface texturing could be sheared off by downslope movements. Therefore, friction testing should include an assessment of the changes to frictional properties with changes in stresses normal to the plane of the material; in a similar manner to changes in rock joint shear strength with the shearing of surface asperities. Friction testing is required, for a range of normal stresses, for all the different geosynthetic interfaces.

It is possible to improve frictional properties too much, so that movement between layers is inhibited and downslope forces are transferred to materials that are not strong enough to carry them. Experience in California has shown that textured geomembranes can be easily ripped by even small downslope forces induced during construction, and some designers have returned to the use of smooth geomembranes on steep slopes (Hlinko et al, 1990).

The use of geomembranes for horizontal liners in the marine areas will require a firm sub-base to be formed, in order that they do not tear as the reclamation settles under the weight of the refuse. Care will be required to ensure that differential settlement is kept to a minimum around any hard spots such as drainage channels and chambers.

The geomembrane that is most widely used around the world at present is high density polyethylene (HDPE), based on low cost and immersion tests of samples that show it to have a good chemical resistance to leachate. The behaviour of HDPE at 40°C. has been investigated by Bush (1990). As HDPE is a plastic with a high degree of crystallinity that is sometimes susceptible to cracking, and has a high coefficient of thermal expansion, manufacturers are currently developing polyethylenes with lower degrees of crystallinity to overcome these problems. They are also looking at the possibility of using polypropylene (PP), which also has good chemical resistance to leachate but is less susceptible to cracking than HDPE.

Other more flexible alternatives, such as polyvinyl chloride (PVC), chlorinated polyethylene (CPE) or scrim reinforced chlorosulphonated polyethylene (reinforced CSPE) also have their disadvantages (in this case the use of solvents for seaming, which are often considered environmentally unacceptable). More expensive ethylene interpolymer alloys (EIA) are available that have some advantages over the cheaper geomembranes; particularly resistance to puncture. Polymer engineers are developing new resins, and new additives, for improved properties and durability. As Hong Kong's new landfills are very large, it would be justified to ask the manufacturers to produce geomembranes tailor made for the conditions specific to these landfills.

Clay

A layer of well compacted homogeneous clay will provide a barrier with a coefficient of hydraulic conductivity to water of 10^{-9} m/sec, without too many difficulties. As the properties of clay are partly dependent on the chemical composition of the clay, it is worthwhile checking the hydraulic conductivity of clay to leachate (Quigley et al, 1987). Clay is also a flexible material that would easily mould itself to the strains induced by the large depths of waste above. It is also resistant to puncture, and will absorb and attenuate the movement of many leachate constituents. However, the greatest drawback to its use in Hong Kong is its lack of availability. There is virtually no clay on land in Hong Kong. There are abundant amounts of marine clay just offshore, but this is not easy to use.

Marine clay has a high water content and is generally very soft. In order to use it as a landfill liner it would need to be dried out, and this would require drying ponds. As large quantities of clay would be required, and drying could be a slow provess, especially in the wet season, the drying ponds would need to cover a large area. With its very high density of population, and mountainous terrain, large unoccupied flat areas are not easy to find in Hong Kong.

Due to its low coefficient of friction, it would be difficult to use clay as a landfill liner on slopes steeper than about 1:3; and it would definitely be unstable on very steep slopes. In addition, its relatively low strength would not allow it to sustain very high stresses from the waste above.

Bentonite Soil Mixtures

Bentonite is a clay mineral which swells when in contact with water, and other liquids. A properly designed and constructed bentonite amended soil can provide a barrier with a hydraulic conductivity to leachate of 10^{-9} m/sec. In order to achieve this, it is very important to ensure that the bentonite and soil are thoroughly mixed, and compacted, with precisely the correct volume of water (Cowland & Leung, 1991). The use of a computer controlled mixing machine, specifically designed for the purpose, is recommended. As supplies of soil are readily available within the site boundaries of the valley landfills, this option has a certain attraction. However, it should be noted that bentonites do not swell readily in the presence of salts, and further work is required to ascertain the applicability of the use of a bentonite liner in the marine areas.

In common with clays, bentonite amended soils are difficult to compact on slopes steeper than about 1:2; although with the soil portion of the mixture consisting of sand they are less likely to provide a slip plane than clays, and they are stronger. They would definitely be unstable on very steep slopes. Bentonites have the advantage that small cracks can be self healing, as they swell in the presence of water. However, this self healing ability cannot cope with very large cracks. Therefore, in common with geomembranes, it is important that bentonite liners are placed on a firm base. In addition, they should not be allowed to dessicate. The rocks, and weathered rocks, within the valley landfills would provide a suitable firm base, but the marine deposits and alluvium would not. A bentonite amended sand would be very compatible with a granular drainage layer, as they are both composes of granular rock particles.

The primary constituent of a slurry trench, from a permeability point of view, is bentonite. This is mixed with either soil, or cement, or both to form a vertical barrier to the movement of leachate.

Bentonite Mats

A recent innovation has been the production of bentonite mats, or geosynthetic clay liners (GCL), which consist of a layer of bentonite powder or pellets sandwiched between two layers of geotextile. One hybrid mat consists of a layer of bentonite granules attached to a geomembrane. These mats are much easier to install than bentonite amended soils, although care is required to effect an impermeable lap. Also, consideration should be given to the coefficient of friction to ensure that the sandwiched layer of bentonite does not provide an unstable slip plane. Their hydration behaviour, their resistance to leachate, their shearing resistance both on the outer surfaces and along the mid-plane, and the permeability of the overlap seams are currently the subjects of research studies. There is also a rapid development taking place of the type and thickness of the bentonite layer, the type of geotextiles used in the sandwich and the factory method of forming a stable mat. Consideration may also be needed as to whether the in-plane transmissivity of the geotextile portions of the mat provide un-intentional flow paths for leachate, before these products are fully developed.

Concrete

Concrete is a material with which the local contracting industry is very familiar. It has a very high strength compared to the other liner options, and can be placed on almost any surface, including vertical slopes. Its strength would allow it to provide a firm base to a marine landfill. Due to the possibility of cracking under high stresses and high temperatures, it would be more permeable than some options, but this can be overcome by facing it with a geomembrane. Concrete can be formed with a smooth surface which would not puncture a geomembrane, but further consideration of their different coefficients of expansion is required. Vertical concrete liners, faced with a geomembrane, have been used to line old quarries for conversion into landfills in Germany.

Asphaltic Concrete

Asphaltic concrete is also a familiar local material. It has a high strength, but cannot be placed on very steep slopes. It is commonly used as an impermeable membrane on the upstream slope of rockfill dams for water retention. As with concrete, the possibility of it cracking under high stresses might make it more permeable than some of the other options, though it is likely to be more resistant to cracking than concrete. Work is currently being carried out to determine a mix design that is resistant to leachate. As long as it can be formed with a smooth surface, it also could be made less permeable by facing it with a geomembrane.

Shotcrete

At first sight, shotcrete is an unlikely landfill liner material. Low quality shotcrete has a high possibility of cracking under high stresses, and therefore of being relatively more permeable than all the other options. However, it is commonly used in Hong Kong to protect steep slopes, because it is very easy to place on those slopes. So it is worthy of further consideration for the valley landfills, or if any old quarries are to be used for landfilling.

If the valley landfill slopes are made near-vertical, and a near-vertical leachate drain is also provided, then as long as the shotcrete is an order of magnitude less permeable than the drain, the leachate will prefer to drop vertically down the drain rather than pass horizontally through the shotcrete. If more impermeability is required, then it may be possible to reinforce the shotcrete with fibres, and also to cover it with plastic or bitumen. A wetter mix may be required than is usually used for slope protection, and the cold joints would need to be replaced by expansion joints using waterstops. Underlying groundwater drainage could be provided with either no-fines concrete or geodrains being placed over major issues of groundwater. Near vertical slopes to valley landfills have the advantage of providing more void space, and of providing more soil and rock from within the site for construction purposes and daily cover.

DRAINAGE LAYER MATERIALS

The alternatives so far considered for drainage layers are granular materials composed of soil or rock, and geodrains.

Granular materials

Naturally occurring river sands and gravels are not as readily available in Hong Kong as in some other parts of the world. However, granular aggregate formed from crushed rock is regularly used as a drainage material. These granular materials are mainly produced from quarries within the granite rocks, and they are similar in appearance to concrete aggregates. They can be graded to have a high coefficient of permeability, and are formed of an intrinsically strong material. Granite rock also offers a high resistance to degradation by leachate. These properties make these granular materials an ideal choice for a long term drainage layer beneath the enormous weight of 120 to 140 m of waste. Their only drawbacks are the difficulties of placing them on steep slopes, and, as they are very angular, the possibility that they could puncture an improperly protected geomembrane liner.

As mentioned earlier, it would be advantageous to increase the void space within the valley landfills by excavation. This opens up the possibility of producing these crushed rock drainage materials on site. These granular materials could then

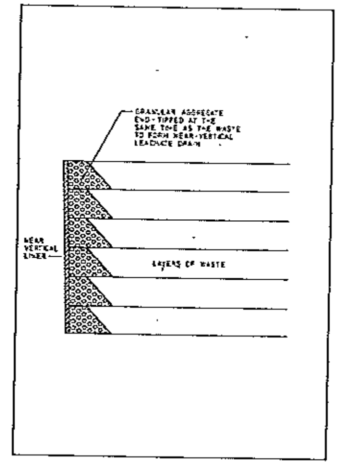

Fig. 6 Method of Forming Steep Leachate Drain with Granular Material

be used for draining the resulting relatively flat valley bottoms, and the marine areas. A potential method for placing granular material for steep leachate drains is shown in Fig. 6.

Geodrains

Geodrains are commonly used as drainage layers in landfills with geomembrane liners in other parts of the world. However, these geodrains are rarely subjected to more than about 50 m of overlying waste. They are usually composed of a sandwich of geotextiles, which act as filter layers, with a geonet or grid of more porous plastic acting as the drainage layer in between. They are sometimes called geocomposites.

Geodrains are easier to install on steep slopes than granular materials, although care is required to avoid tension under self weight, and a smooth surface needs to be provided for them; in common with geomembranes. Some of them suffer from degradation when exposed to ultra-violet light, and care is required during construction to ensure that they are kept protected from the tropical sunshine (Brand & Pang, 1991). As they are a relatively weak material, they are easily crushed, and their hydraulic conductivity will decrease with stress. Most of them are reduced to a hydraulic conductivity of zero under a normal stress of 650 kPa, and will therefore cease to reliably function as a drainage layer under more than about 50 m of waste.

They are very suitable for use as drainage layers in the higher regions of the valley landfills where depths of waste are below 50 m. No doubt the manufacturers of these products will soon produce geodrains that can function under larger normal stresses.

LINER LEACHATE COMPATIBILITY

A very important element of the design of a liner and drainage system is to ensure that they can continue to perform their required function after a number of years of exposure to the leachate being produced by the landfill. Early work on the durability of liner materials was carried out by exposing these materials to various chemicals and hazardous wastes (Haxo, 1981 and Haxo et al, 1986). However, these liquids were often much stronger than those found in municipal landfill leachate. The current method of assessment of liner leachate compatibility is to immerse samples of the liner in baths of leachate recovered from the existing landfill, or from landfills similar to the planned landfill. After a period of exposure, these samples are taken out of the leachate bath and subjected to strength tests to determine their deterioration (Landreth, 1990).

For geomembranes, this method of assessment has been formalised in the United States Environmental Protection Agency (US EPA) Method 9090 (1986). In this test, samples of the liner material are immersed in baths of leachate at 23°C. and 50°C., or higher temperatures if thought necessary, for a minimum period of 120 days. Comparison of measurements of the membrane's physical properties, taken periodically before and after contact with the waste fluid, is used to estimate the compatibility of the liner with the waste over time (Landreth, 1989). This method works well for materials that are not affected by exposure to the leachate, but can pose difficulties of interpretation for materials that show some deterioration (Dudzik & Tisinger, 1990). In addition, it is a time consuming and expensive exercise, and it is difficult to explain the rationale of using strength tests to determine long term permeability to a non-specialist client. The American Society for Testing and Materials (ASTM) is currently revising this test method.

The US EPA Method 9090 does not cover any type of liner material other than geomembranes, or any drainage materials. The longevity of the leachate drainage materials is as important, if not more important, than the liner materials. In addition to durability, they must not become clogged by the leachate so that they will no longer perform a drainage function. However, this issue has only relatively recently been addressed (Rohde & Gribb, 1990 and Koerner & Koerner, 1990). Attention is now being focused on test methods for other materials as well as geomembranes (Landreth, 1990 and Verschoor et al, 1990).

GUIDANCE DOCUMENTS

The background to landfill leachate containment is summarised in Milligan (1983). A useful introduction to current practice in the U.S.A. is to be found in Oweis & Khera (1990). The United States Environmental Protection Agency (US EPA) has produced a large volume of guidance documents, including (US EPA, 1988a, 1988b, 1989a, and 1989b).

The American Society for Testing and Materials (ASTM) are producting a

large number of standards relating to landfills, including ASTM (1991); which lists no less than 70 other related ASTM standards. ASTM committees D18 and D35 are currently producing a large number of standards relating to the testing of clay liners and geosynthetics, respectively. The U.S. National Sanitation Foundation produced a standard for geomembranes (NSF 54, 1983).

A good introduction to geosynthetics is to be found in Koerner (1986). In addition, ASTM have produced a number of Special Technical Publications (STP), in book form, on geosynthetics. The Geosynthetic Research Institute (GRI), in Philadelphia, has produced a number of reports on the properties of various geosynthetic products.

COMPARISON WITH EUROPE

In Germany, as in the U.S.A., protection of groundwater is paramount, as it is the primary source of drinking water for both countries. The Germans have also tended towards clay and geosynthetic composite liners, especially in the flat and industrialised north, but have adopted slightly different thicknesses and practices (Burnett, 1991). In the more hilly southern parts of the country, different liner materials have been used. Whereas the Americans have placed a certain amount of reliance on leakage detection, followed by remedial action, the Germans have concentrated more on the robustness of the liner design.

There has been a wide variation in practices across the rest of Europe, although with proposed EEC legislation this variation will become less (German Geotechnical Society, 1991). It should be noted that there is a wide variation of conditions across Europe, which has given rise to this variation in practices. In the wetter western countries of Britain, France and Portugal, 70% of drinking water is obtained from surface reservoirs in carefully guarded catchments. In comparison Germany, Denmark and Italy obtain 70% of their drinking water from groundwater. Some parts of western Europe have large thicknesses of low permeability clays beneath their landfill sites, compared with more permeable sandy material in north central Europe.

For municipal landfills, the French have until recently only stipulated a 5 m thick soil liner with a coefficient of permeability of 10^{-6} m/sec. For hazardous waste landfills, they have stipulated 5 m of clay with a coefficient of permeability of 10^{-9} m/sec, to which they have recently added a geomembrane (Street, 1991). The Italians have not adopted a unified approach until recently, but the emphasis has been a multi-barrier approach to protect their groundwater supplies with double geomembrane liners, or clay and geomembrane composites. In Britain, there has been a reliance on the low permeability and the attenuation properties of the underlying clay soils. Thus leachate containment has not been practiced until very recently, and landfills have been designed to allow the leachate to dilute and disperse into the underlying ground (Leonard et al, 1991).

In the Netherlands, the emphasis has been on the capping of landfills to prevent infiltration of rainwater, and thus minimisation of leachate generation, with the bottom liner being designed to have a maximum percolation rate of 20 mm/year. With large parts of the country being covered with sandy soils, bentonite amended soil liners have been used extensively. Much of the development work on the use of bentonite liners has been undertaken in the Netherlands and they continue to be used, in combination with slurry trench cut-off walls with geomembrane inserts. The use of an additional geomembrane on top of the horizontal bentonite amended soil liners, to form a composite, is becoming more common.

CONCLUSIONS

There is a wealth of useful experience available from the extensive development of landfill liner design in North America. However, the practice of placing very large depths of waste in steep sided valleys and on soft marine reclamations, in a hot wet climate, means that the appropriate geotechnology for Hong Kong's landfill liners will inevitably be a little different from the U.S.A.. These differences may be common to other South East Asian areas (especially Japan, Korea and Taiwan) where topography, climate and types of waste are similar to Hong Kong.

The aim of a lining and drainage system in Hong Kong's steep valley landfills is to husband the flow of leachate down to the open valley mouth, where it can be effectively dealt with. With natural side-slopes of 25° to 40° rising from near sea-level to a height of a few hundred metres, it may be more productive to concentrate on providing a good drainage system for the leachate rather than simply trying to place standard North American liner systems on much steeper slopes than they were originally intended for. The steep natural slopes allow the concept of near vertical drains to be introduced. At the very least, the slope stability aspects of the standard systems need to be carefully appraised.

The base of a valley landfill, and the lower portions of the side-slopes, will be subjected to the weight of an enormous depth of refuse, that may be decomposing at higher temperatures than have been considered in standard designs elsewhere. The use of composite liners (a liner comprising two layers of different materials in contact with one another) will provide the best option of forming a liner that has the optimum impermeability and strength. The normal concept of a composite liner is for the secondary liner to reduce the flow of leachate out of the landfill, and then the primary liner to reduce it even further. This concept can be expanded in Hong Kong to include the need for one component of the system to provide strength, in order to withstand the very large depths of overlying waste. The need for the drainage system to survive these large weights of overlying waste also needs to be carefully considered.

From a geotechnical viewpoint, the design considerations for the marine landfills are quite different from those of the valley landfills. The low strengths of the marine deposits, and the underlying alluvium, give the designer considerable problems in maintaining the stability of large depths of refuse. In addition, the

variable compressibility of these soft soils will easily lead to either tearing through stretching, or cracking through flexing, of conventional horizontal liners. It may be easier to form a vertical barrier to leachate flow. It should be noted that with Hong Kong's dependence on mariculture, the consequence of failure of a marine liner is high.

During the design of a landfill liner and drainage system, it is important to ensure that the various components of the system are compatible with each other. For instance, a granular drainage layer composed of sharp angular crushed rock could easily puncture an improperly protected geomembrane. Also, greatly differing coefficients of expansion between one component and another could cause problems during construction. With careful attention to detail, though, it should be possible to come up with new and improved systems for coping with the large depths of waste planned for Hong Kong's valley and marine landfills.

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