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GEOTECHNICAL AND ENVIRONMENTAL INVESTIGATIONS AT TWO EXISTING HONG KONG LANDFILLS

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SYNOPSIS

In and around the urban area of Hong Kong, a number of completed landfills are sited close to existing housing estates and other proposed developments. Many of these landfills were developed at a time when the associated hazards were not fully understood; they consequently lack the necessary measures to contain leachate and control landfill gas.

Two existing landfills in Tseung Kwan O (previously known as Junk Bay) were investigated over a six-month period during 1989 to 1990, primarily to provide information on the leachate and landfill gas characteristics of these two sites.

One of the two landfills investigated is partially closed, and a large proportion has been capped; the other is operational, and due to be completed by 1993. A series of drillholes were sunk around the larger of the two landfills, and boreholes were put down into the waste at both sites. Samples of landfill gas, landfill leachate, groundwater and waste were collected and analysed. These results were augmented by on-site measurement of landfill gas concentrations and pressures. Selected boreholes were also used for landfill gas pumping tests. During the investigations, particular attention was given to identification and potential for landfill gas migration away from the landfills as further developments are proposed in close proximity to them.

The results of the investigations are summarised, together with the implications for leachate collection and treatment, and for landfill gas control and utilisation.

INTRODUCTION

Hong Kong, located on the south coast of China, is well known as one of the world's busiest ports; a key financial centre; and, for its densely populated urban areas with many multi-storey buildings.

Hong Kong has a population of about 5.8 million and a total land area of 1,075 sq km. Over 70% of the total area is undeveloped with 400 sq kms designated as Country Parks, protecting woodlands and wildlife in scenic steep and hilly terrain, and providing a valuable recreational resource. Consequently most of the develop-

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ment and population are concentrated within the remaining 30% of relatively flat land along the coast formed over the years by levelling low-lying foothills and reclaiming from the sea.

In 1990, Hong Kong was generating 24,000 tonnes of municipal solid waste per day comprising: household refuse; waste from numerous commercial buildings, shopping complexes, restaurants and hotels; chemical and trade waste from light-industrial factories and manufacturing premises; and construction waste from demolition and building sites. Specifically excluded from these statistics are coal ash, mainly pulverised fuel ash (PFA), from coal-fired power generation; waste from pig and chicken farming in rural areas; and sludge from sewage and water treatment.

A large proportion of this waste, approximately 16,000 tonnes per day, is delivered to, and placed, in landfills. The balance is disposed of separately: a small proportion of household waste is incinerated, by out-dated plants which are currently being phased out (2,000 tonnes per day); and about 6,000 tonnes per day is recycled, a significant proportion being exported overseas to other South East Asian countries as scrap metal and scrap paper.

EXISTING LANDFILLS

At present there are 13 landfills in Hong Kong, of which 10 are completed, and 3 are in operation. Collectively they occupy a total land area of about 250 hectares.

Although some of these landfills are located in the rural New Territories, nearly 50% of these landfills are located in the densely populated urban area sited close to housing estates and other developments. Many of the landfills were developed at a time when the associated hazards were not fully understood and lack the necessary measures to contain leachate and control landfill gas. They are a potential threat to the environment and the health of the local community.

Already one of these sites at Sai Tso Wan near the Lam Tin Mass Transit Railway station has been retrofitted with landfill gas extraction wells and associated pumping facilities. Other sites, one already developed as a park, are progressively being investigated; and comprehensive recommendations made on:

- safety measures
- slope stability
- abatement of pollution caused by discharges from each site
- potential for landfill gas utilisation
- restoration including landscaping and planting
- opportunities to exploit these sites for community use (with particular consideration of the potential for private sector involvement).

This paper describes investigations commissioned by the Environmental Protection Department (EPD) at two existing landfills, which are located at Tseung Kwan O (previously known as Junk Bay) in the south eastern New Territories of Hong Kong.

The specific objectives of these investigations were two-fold:
- to provide information on the landfill gas and leachate characteristics at the two sites
- to determine the suitability of land adjacent to the landfills for development

LANDFILLS HAZARDS

General

Over the last 5 to 10 years, authorities worldwide have recognised that large landfills in urban areas can be a potentially serious threat to public health, because of the risk of landfill gas migrating to occupied buildings. Additionally, threats to the environment exist if leachate escapes into groundwater or into surface water in an uncontrolled fashion. Determination of the fate of these contaminants is important to establish whether a major public health risk exists. Other impacts on the local community may occur in the form of unpleasant odours, or nuisance from rodents and birds.

When assessing hazards associated with landfills, the risks which may accrue from leachate are often considered to be less than that from landfill gas, as the latter has the potential to explode, and cause asphyxiation. As a result, emergency measures to control gas frequently have to be implemented at landfill sites, whereas leachate control measures are usually dealt with less urgently.

The recognition of these potential problems in Hong Kong has led to the implementation by the EPD, of a consulation zone extending some 250 m out from the boundary of all urban landfill sites. Within this zone, developers must consult with EPD on the need for specific building protection measures to guard against the possibility of landfill gas migration and entry of gas into buildings.

Landfill gas

Landfill gas, consisting predominantly of a mixture of methane and carbon dioxide, is produced during the breakdown of organic material present in the waste. Trace levels of hydrogen, hydrogen sulphide, mercaptans and ethylene can also be present. Some chemicals within the gas may give rise to odours, while other components may be corrosive. When combined with air, landfill gas forms a mixture, which, under certain conditions, can explode when exposed to a source of ignition. Landfill gas accumulating in a restricted space, such as a building or a room, also presents a risk of suffocation because of the reduction in the proportion of air, and toxic effects due to carbon dioxide. Excess carbon dioxide can also displace soil oxygen and cause damage to vegetation.

Leachate

As solid waste within a landfill breaks down, it releases a number of highly polluting materials which can dissolve in any water that infiltrates or is present in the landfill, to generate leachate, a highly polluting liquid. Water can enter a landfill either as direct rainfall on the waste, or as surface water run-off from surrounding higher land, or as groundwater through infiltration from the surrounding strata, or already be present if waste is tipped into seawater. The leachate that is formed can then percolate through the waste, and unless it is controlled, it will seep out of the landfill and pollute any bodies of water it mixes with.

As drinking water in Hong Kong is either provided by surface collection of run-off using catchwaters and reservoirs, or piped in from China, rather than being pumped from groundwater sources, the contamination of groundwater by leachate has not in the past raised major concerns. However increasing attention is being paid to the pollution of seawater. As inorganic nitrogen levels in seawater are raised by various forms of pollution (including contaminating leachate from landfills), the nutrient content of a water body can reach such a high level that primary organisms, such as algae, experience population explosions causing eutrophication, more commonly known as "red tides". As the organisms in these population explosions die and decay, the water can be stripped of oxygen, resulting in the death of fish and other marine life.

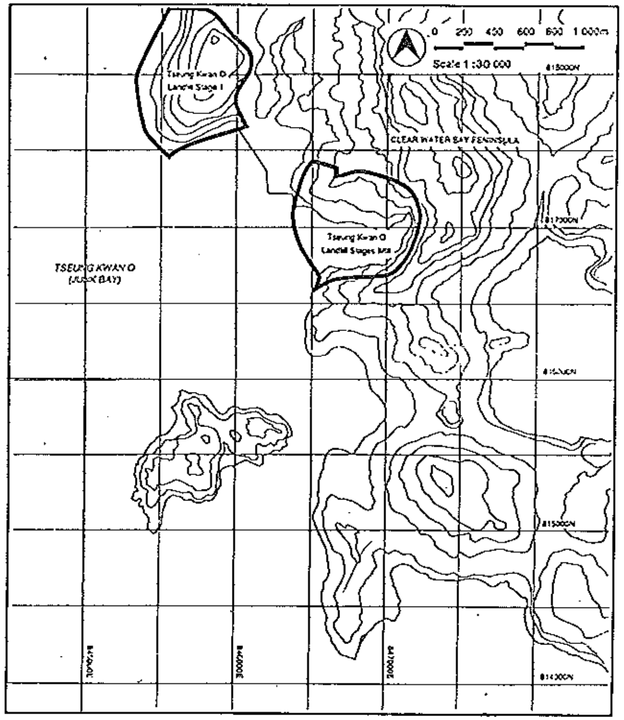

Fig. 1 Site Location

The majority of Hong Kong's existing landfills are not lined and leachate is generally free to enter the groundwater regime under the landfill, or escape into the sea in the case of sites that are close to the coast (of which there are several, including those at Tseung Kwan O). Some landfills include an attenuation zone adjacent to the site boundary; other designs include limited lining and collection of the leachate, with recirculation onto the landfill as a means of dispersal, or disposal to a nearby sewage treatment works.

WASTE INPUT AND SITE CONSTRUCTION

Stage I Landfill

The first landfill at Junk Bay (now referred to as Tseung Kwan O Landfill Stage I) was sited on the east coast of the bay well away from the urban area of Kwun Tong. The site was commissioned in 1979, at a time when this part of Hong Kong was a rural backwater in the New Territories of Hong Kong. The area had poor road access, and was well-known for its ship-breaking; and, apart from the landfill, there were no specific plans for future developments.

The site was predominantly reclaimed from the sea and subsequently received a total of approximately 12 million cubic metres of waste before being temporarily closed in 1989.

In the intervening 10 years after 1979, the rural character of the area has changed significantly (a typical phenomenon in many other parts of rural Hong Kong). By 1989 the construction of a new town (known as Tseung Kwan O) with a projected population of 400,000 was well advanced, with community and transport infrastructure requirements to service this population being provided, and new industrial developments planned.

By 1992 the Stage I Landfill was no longer receiving waste, and parts of the site are now capped, restored and grassed. Other areas on the south and south-east of the site will be used for further waste disposal commencing during 1992-93. Little preparation was carried out for the Stage I Landfill, with waste being deposited onto marine muds, and directly into water, behind an enclosing seawall (Yip, 1990). This landfill was not designed as a containment site in which leachate and landfill gas would be controlled, but relied on attenuation of landfill leachate by internal bunds and a 17.5 m wide "soil" layer behind the seawall. There was clear evidence during the study that leachate was escaping through the seawall and entering the waters of Tseung Kwan O bay. At the time it was constructed, no monitoring facilities were incorporated into the landfill to measure leachate and landfill gas emissions.

The capping on the Stage I Landfill comprises a layer of low-permeability completely decomposed rock (volcanics and granites) which serves to minimise infiltration of rainfall into the waste, and hence limit the generation of potentially-polluting leachate. Research on other landfill sites in Hong Kong has shown that a very small

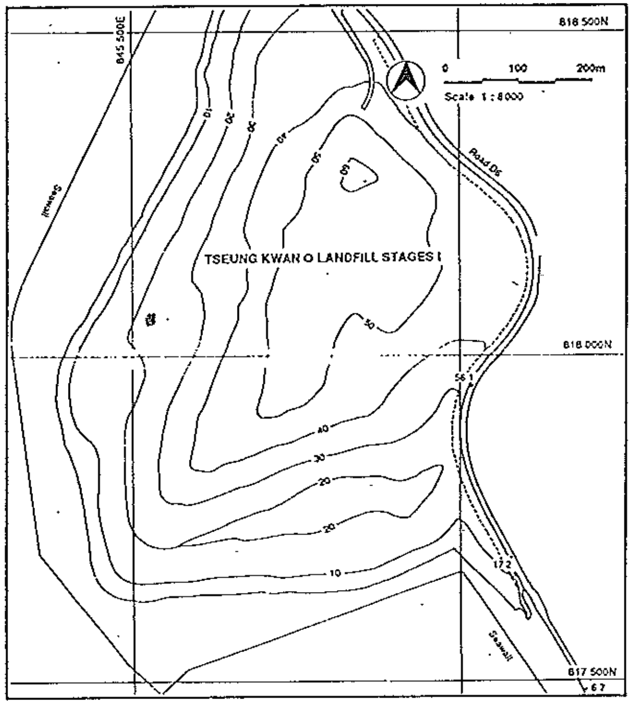

Fig. 2 Tseung Kwan O Landfill Stage I

proportion of Hong Kong's annual mean 2,220 mm of rainfall infiltrates through this type of capping (Mattravers and Robinson, 1991). In addition this capping goes a long way to contain the landfill gas within the waste, though at the risk of encouraging lateral landfill gas migration. Following the capping, trees and shrubs were planted to provide landscaping, and to enhance water loss by evapotranspiration; and an extensive network of concrete drainage channels constructed across the cap to control erosion and aid the shedding of surface water.

Stages II/III Landfill

The second landfill (known as the Tseung Kwan O Stages II/III Landfill), which is within one kilometre to the south-east of the Stage I Landfill, came into operation during 1989. This site was planned with a total capacity of 12.6 million cubic metres, and will remain operational during 1992, receiving 10,000 to 12,000 tonnes of waste each day; based on this intake the available void space is expected to be exhausted in 1993.

Unlike the Stage I Landfill, the Stages II/III Landfill extends only in part over what was the sea. Situated in a valley, a much shorter seawall was required to form

the seaward boundary of the landfill. Upgrading of landfilling techniques in Hong Kong, and the progressive development of Tseung Kwan O, resulted in this site incorporating additional facilities compared with the Stage I Landfill. For instance the seawall formed part of a leachate collection system; drainage channels were constructed on the hillside around the perimeter of the landfill prior to waste disposal to minimise surface water entry into the waste; and groundwater monitoring drillholes were installed at an early stage, and sampled regularly to provide information on any impacts of the waste disposal operations on local groundwater resources.

The Stages II/III Landfill site was partially lined to prevent leachate entering local groundwater, and measures provided to reduce leachate migration westwards through the seawall into what is to become an industrial area. To achieve this, the landward side of the seawall was covered with a 15 m wide layer of completely decomposed volcanic rock (cdv), which was in turn covered by a 3 m wide "interception" zone comprising coarse aggregate within which a continuous length of perforated pipe was installed to form a leachate collection drain. A collection system was installed at the toe of the landfill to drain collected leachate under gravity into the Tseung Kwan O Sewage Treatment Works, which is located adjacent to the northern boundary of the landfill.

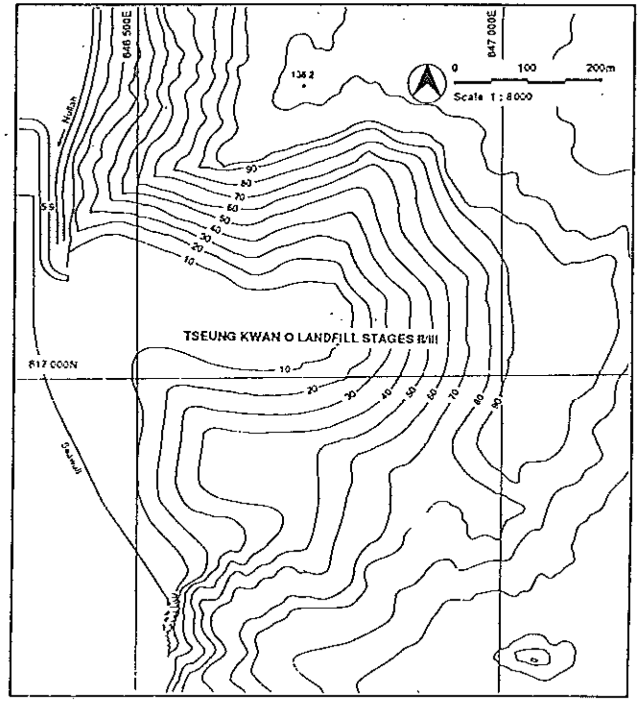

Fig. 3 Tseung Kwan O Landfill Stages II/III

TSEUNG KWAN O LANDFILLS : SCOPE OF INVESTIGATIONS

23 boreholes through waste and 35 drillholes through the rock formation adjacent to the landfills were completed in 1989 & 1990 to provide facilities for:

- groundwater monitoring
- leachate monitoring
- landfill gas pumping trials
- landfill gas monitoring, within and outside the landfill boundaries.

Boreholes

Boreholes through waste were drilled using rotary methods with compressed air as the hole cleaning medium. Three types of borehole completion were used, depending on the monitoring requirements:

- *Combined leachate/landfill gas monitoring boreholes*

  These holes had a minimum diameter of 200 mm and included twin standpipes, 75 mm and 50 mm diameter, to monitor respectively leachate and landfill gas. Typically these holes were terminated up to 5 m below the base of the waste; the leachate standpipe was sized to enable leachate samples to be collected using a submersible pump inserted down the standpipe.

- *Landfill gas extraction boreholes*

  These holes had a minimum diameter of 225 mm and were terminated up to 5 m below the base of the waste. Each hole included a 125 mm uPVC perforated extraction pipe which extended from ground level to at least 500 mm above the higher of either the standing leachate/groundwater level or the base of the waste.

- *Landfill gas monitoring boreholes*

  These holes had a minimum diameter of 200 mm, included a standpipe to monitor landfill gas, and were terminated near the base of the waste.

It had been planned to use 300 mm diameter holes for the gas extraction boreholes. However, because the waste materials contained a significant proportion of construction debris, further penetration at 300 mm was not possible beyond depths of 10 to 14 m below ground level. Below this depth the holes were progressed at a diameter of 225 mm, using an eccentric drill bit, and a 200 mm temporary casing. Compared with percussion boring methods, used extensively in UK for landfill investigations, the main disadvantages of this method are inferior definition of waste types, poorer sample recovery and difficulty in the identification of groundwater and leachate horizons.

Drillholes

Separate drillholes were sunk beyond the boundary of the deposited waste around each landfill site for the monitoring of groundwater and landfill gas:

- *Landfill gas monitoring*

  These holes were drilled at H-size (114 mm) using rotary air-flush methods, and a 50 mm diameter standpipe installed to detect landfill gas.

- *Groundwater monitoring and sampling*

  These holes were drilled at S-size (168 mm) using water-flush methods, and a 75 mm diameter standpipe installed to monitor groundwater levels and to sample groundwater.

Other Investigations

On the Stage I Landfill the lateral extent of waste was established by trial trenches 3 to 4 m deep excavated with a backhoe.

The fieldwork also included a walk-over survey, using Gas-tec portable gas detection equipment (manufactured by Research Engineers Ltd of UK), to measure landfill gas concentrations over the surface of each landfill and its immediate vicinity. The same equipment was used to measure gas concentrations in boreholes and drillholes.

Limited soil probing was also carried out on the Stage I Landfill using a searcher bar and an Oxygas Gascoseeker (manufactured by Gas Measurement Instruments Ltd of UK) to measure landfill gas concentrations, but because of the difficulties of probing the compact surface soil layers this was not continued. The same gas sampling equipment was also connected to the gas-tight tap on each landfill gas monitoring hole to measure methane and oxygen concentrations.

Carbon dioxide concentrations in boreholes and drillholes were measured using Drager gas detection tubes (manufactured by Dragerwerk Ag Lubeck of Germany), by drawing a fixed amount of gas through them. These measurements were performed primarily in holes showing oxygen depletion.

Landfill gas pressure measurements were carried out using a portable digital micromanometer, mainly to assess the build-up of positive pressures within the body of the waste.

Sampling

Bulk samples of waste were taken from boreholes, double wrapped and sealed, and refrigerated prior to laboratory analyses. The following parameters were analysed:

- moisture content was measured to determine whether the waste samples were fully saturated and to determine whether the moisture content was at levels conducive to landfill gas production.
- cellulose and lignin: the different rates of decomposition of these components were measured to give an estimate of the degradation potential of the waste, and hence the potential for future landfill gas production.

* acid digestible fibre: this percentage was measured to give an estimate of degradable carbon-based materials in the waste.
* calorific value was measured to provide an indication of the ability of the waste to sustain a fire, and an independent measure of the organic matter present, and hence the potential for future landfill gas production.

Other sampling carried out during the investigations included:

* groundwater from drillholes around the landfills: to obtain background groundwater quality data
* landfill leachate from boreholes in the landfills: to establish its chemistry, and provide information on its mixing and dilution with groundwater and/or seawater.
* landfill gas from boreholes in the landfills: for measurement of gas components, providing a more comprehensive gas analysis than achievable with portable equipment and a calibration reference for on-site measurements.

Leachate and groundwater in boreholes and drillholes were sampled using a 50 mm diameter submersible pump which was able to pump from depths up to 30 m below ground level. For this purpose a QED model HR4105D portable purging and well development pump was purchased by EPD and shipped to Hong Kong as part of the study. Samples collected were tested in a Hong Kong laboratory for a range of constituents : sodium, potassium, calcium, magnesium, chloride, sulphate, carbonate alkalinity, nitrate, ammonium, pH value, electrical conductivity, alkalinity, Biochemical Oxygen Demand and Chemical Oxygen Demand.

Landfill gas samples were collected from boreholes and drillholes for laboratory analyses of major gas components (oxygen, nitrogen, methane, carbon dioxide and hydrogen). The samples were collected using a manually operated vacuum pump, in gas-tight sampling bombs. In addition, two further gas samples were collected for the analyses of trace organic gases to provide the following information:

* toxicity and odour of trace components
* potential corrosiveness of gas in relation to future migration control and extraction equipment
* data on the extent of waste degradation

Gas Pumping Trials

In addition, landfill gas pumping trials using a Hofstetter gas pumping rig were carried out on three boreholes on the Stage I Landfill, and two boreholes on the Stages II/III Landfill, to provide information on gas production rates of the waste and the potential for gas extraction and utilisation.

For these trials additional instrumentation, comprising drive-in piezometers penetrating the landfill capping, was installed in the vicinity of the five gas extraction boreholes. They were located at different distances (between 5 and 50 m) from the extraction point to identify the zone of influence caused by the pumping with respect to time and distance from the borehole. During each test, measurement of pressure, oxygen, methane, carbon dioxide, temperature, and gas flow rate was carried out. Boreholes were pumped on an uninterrupted basis for periods ranging from three to twelve days; the rig being left unattended at night to pump continuously.

RESULTS OF THE INVESTIGATIONS

Waste Deposits

Waste thicknesses between 8 and 41 m and 9.5 and 27 m were proved on the Stage I and Stages II/III Landfills respectively. Around the flanks of the Stage I Landfill, moderately and highly decomposed volcanic rocks and dark clay marine deposits were identified beneath the waste at levels close to or below Principal Datum. Particularly in the southern part of the site, waste was deposited below sea level, to a maximum depth of approximately -8 m PD. Access and operational restrictions meant that boreholes on the Stages II/III Landfill were sited in completed areas in the south western part of the site. Waste thicknesses in these areas are less than in those further to the east. All of the waste deposited on this site was at levels above 5 m PD.

Groundwater Quality and Levels

Water levels measured in boreholes constructed through waste indicated relatively high elevations within underlying rock strata in areas of greatest waste thickness beneath completed parts of the landfill. Around the margins of the landfills, the levels were lower, but up to 12 m above the bottom of the waste deposit.

The Stage I Landfill data showed wide ranges in water quality, primarily as a function of proximity to the sea. Boreholes around the margin, and those completed over the lower-lying southern area all recorded (with one exception) chloride concentrations greater than 15,000 mg/l. Since waste deposited in this area was proven to extend to below local mean sea-level, it is partly saturated and capable of being leached by seawater, thus releasing contaminants into the sea. Sampling at different tidal stages showed that water quality could change relative to the tidal cycle. Closer proximity to the sea resulted in a more marked marine influence, as might be anticipated. Within the heart of the Stage I Landfill, the marine influence was less, with ammonium concentrations beneath the waste typically between 500 and 1,900 mg/l (as N) with sodium and chloride much lower than in peripheral boreholes.

Within and beneath waste deposits on the Stages II/III Landfill, which were deposited above levels of tidal influence, analyses generally showed concentrations for landfill leachate with elevated levels of all major constituents, particularly ammonium, chloride, sodium and potassium. One off-site monitoring drillhole indicated significant contamination, illustrating the potential for lateral leachate migration where a large thickness of waste is placed against unlined valley sides.

Waste Analyses

Published data for domestic refuse in the United States and Europe suggest a starting point in fresh refuse of about 40% cellulose, and a cellulose/lignin ration of about 4.

The cellulose content of samples from the Stage I Landfill ranged between less than 10% to greater than 70%, indicating the variability of the waste. In addition, sample selection procedures adopted on site mean that a factor of (possibly) 0.5 should be included for the analyses to be related to the total waste volume, since, for example, samples of generally inert materials such as natural fill deposits and construction waste, which comprised approximately half the waste input, were excluded from the laboratory analysis. Lignin content was consistently very low, and possibly indicates different raw materials compared to waste in the US and Europe, eg timber for paper manufacturing, in SE Asia.

The moisture content determinations for both sites was significantly lower than typical values measured for waste in UK. This feature is likely to be caused by a combination of the following factors:

- Investigations were carried out during the dry season;
- Final capping and surface water drainage measures constructed over a large proportion of the Stage I Landfill effectively reduce the infiltration of rainfall;
- The deposited waste was relatively dry;
- High temperatures (approximately 50° C) recorded within the waste encourage moisture loss;
- Air flush method of drilling;
- High disposal rate, with the absorptive capacity of the waste exceeding rainfall.

The moisture contents observed were generally below those considered necessary to exceed the absorptive and field capacities of waste and thereby result in leachate generation (Department of Environment, 1986). Results were variable however, and the onset of leachate generation is unlikely to take place in a constant fashion over the landfill. Also, the low moisture contents would not be conducive to optimum microbial activity and together with high temperatures would encourage steady gas production over several decades once the putrescible material has degraded in the first few years after waste deposition.

The most notable feature of the waste composition was the low lignin content. The cellulose/lignin ratio consequently reached higher than the maximum of 4 previously observed in the USA, UK and Europe, with a mean of 3.9 for all samples. The fresher waste sampled in the Stages II/III Landfill had a mean cellulose/lignin ratio

of about 11 which is an unprecedented figure. Use of the cellulose/lignin ratio to predict the state of degradation of waste was first developed in the United States (Ham & Bookter, 1981). The years of experience of using the method in the UK have shown it to be reliable, providing the uncertainty from waste sampling is taken into account. The ratio is dominated by paper and wood pulp from Northern European and North American softwoods which are considered likely to have a different compositional analysis to paper manufactured in Taiwan, Korea, and Japan which accounts for the majority of imported paper products to Hong Kong. The conclusions drawn were as follows:

- Specific data on cellulose and lignin content of waste arising in Hong Kong is required before accurate assessments of the state of degradation can be made using cellulose/lignin ratio data;
- Hong Kong waste contains a significantly lower lignin content than equivalent waste from Northern Europe and North America;
- The lower lignin content may be due to different tree species dominating the composition of paper and paper products;
- A comparison of the cellulose/lignin ratio for the Stages I and II/III Landfill sites indicates that the waste in the Stage I Landfill is substantially older and more degraded than in the Stages II/III Landfill, representing a loss of up 60% of the degradable refuse mass;
- The cellulose content is relatively high compared with published data, which suggests that cellulose and lignin together, and hence the paper products proportion in the waste is similar in Hong Kong to Northern Europe/North America.

The mean ratio of acid digestible fibre (ADF) to cellulose and lignin on the Stage I Landfill was 1.3, which is typical for mature waste. The result confirmed that there was no significant component of degradable material in addition to cellulose in the waste in the Stage I Landfill, and lent confidence to the derivation of gas production data from the cellulose content. Although this ratio was found to be lower in waste samples from the Stages II/III Landfill site, the results did not suggest that the fresher waste contain any major gas producing component other than cellulose.

Gas production potential was estimated from the waste analysis results to be between 100 to 190 cum/tonne for the Stage I Landfill, with 50 to 95 cum/tonne collectable gas remaining. Similar calculations for the Stages II/III Landfill gave an estimate of 150 to 300 cum/tonne, with 100 to 190 cum/tonne collectable gas remaining.

Gas Monitoring

Over the restored part of the Stage I Landfill, high (> 5,000 ppm) concentrations of methane were detected in cracks in cover materials and surface water drainage channels, though the frequency of these discontinuities was small. Typically low concentrations of landfill gas were discharging over the bulk of the site, indicating that the capping is effective in containing much of the gas within the site and restricting its escape into the atmosphere. In consequence, and as pressure measurements confirmed, there is the potential for the build-up of positive gas pressures within the landfill, and for its lateral migration beyond the site boundary, both seaward and landward.

Off-site gas monitoring in drillholes to the east of the Stage I Landfill indicated some impact from the landfill, as evidenced by reduced oxygen concentrations and carbon dioxide levels typically between 2 and 5%. No methane was detected, indicating its oxidation to carbon dioxide.

On site gas monitoring at both sites showed consistent quality landfill gas of approximately 50% methane and 45% carbon dioxide, with oxygen concentrations remaining below 1%. The highest borehole pressures were recorded in capped areas with the deepest waste; higher pressures (up to 110 Pascals) in the Stages II/III Landfill being attributed to a greater gas generation rate from the newer waste. Gas temperatures were typically about 50°C in restored parts of the sites, and slightly lower in uncapped areas. This temperature is common for dry sites in warm climates with high rates of waste input, and has been recorded in landfills in California, USA. Capping tends to insulate the waste and retain heat, while uncapped areas of shallow waste are more susceptible to ambient conditions (air and sea temperatures), with resulting lower gas temperatures.

Gas pumping trials formed a significant part of the investigations. Pumping was carried out at a rate of approximately 440 cum/hour and produced radii of influence between 0 and 35 m for boreholes on the Stage I Landfill. Similar results were recorded on the Stages II/III Landfill. All boreholes recovered rapidly to pre-pumping positive pressures when extraction was stopped which, together with observed relatively low suction pressures, indicates high gas permeability within the waste.

Using the data obtained from the pumping trials, assuming a conical radius of influence increasing to a depth of 30 m, and assuming landfill gas generation takes place for 20 years with 4 times more gas generated in year 1 than year 20, the remaining collectable gas from the waste was calculated in the range of 120 to 180 and 280 to 350 cum/tonne of refuse for the Stage I and Stages II/III Landfills respectively. These figures did not correlate well with those obtained from waste analysis and the assumption regarding gas generation rates over a 20-year period were reconsidered.

The waste analyses of samples from the Stage I Landfill did not record a significant element of putrescible waste indicating that it had degraded rapidly to give a high initial rate of gas production. A significant proportion of paper and fibre with low moisture content remain, which will give a low generation rate over a long period of time. The gas generation profile is considered to be steeper, during the first few year, falling to a low generation rate for longer than 20 years. If this is the case, the remaining collectable gas volume will be lower than quoted above, and nearer to

those calculated from the waste analysis. The collectable yield for the Stages II/III Landfill is higher than for the Stage I Landfill because the waste is fresher, and possibly because there is a greater proportion of degradable waste within this site.

CONCLUSIONS

The Stage I Landfill showed little evidence of groundwater contamination on its landward side, but the analyses confirmed that the leachate was being diluted by seawater on the seaward boundary. Along the seawall, marine pollution was occurring with leachate entering Tseung Kwan O bay on the ebb tide of each tidal cycle. The leachate quality was indicative of a methanogenic leachate typical of Hong Kong waste, greater than one year in age.

In turn the Stages II/III Landfill with its leachate collection system was shown to be generating significantly less marine pollution. Quality was typical of Hong Kong leachates, with high concentrations of ammonia and chloride.

Large quantities of landfill gas were shown to be generated in both landfills, generally with a consistent quality comprising 50 to 55% methane, 35 to 45% carbon dioxide, and less than 1% oxygen. In pumping trials, the gas yield exceeded the capacity of the pumping rig at some locations. The gas pumping trials and waste analyses were used to estimate the long-term gas generation potential, and indicated that the degradation of waste on the Stage I Landfill was entering a prolonged period of gas yield, but at lower rates than previously, whilst the Stages II/III Landfill was still generating gas at high rates, retaining the bulk of its gas production potential. The remaining gas in the Stage I Landfill was estimated to be between 50 to 95 cum/tonne, whereas in the Stages II/III Landfill between 100 to 190 cum/tonne was estimated.

Trace gas analyses were typical of those derived from mature waste, with apparent enhanced corrosion potential.

The results of the walk-over gas surveys and pumping trials indicated that the temporary and permanent capping layers on both landfills were effective in preventing significant quantities of landfill gas venting to the surface, but as a consequence there was enhanced potential for lateral migration of landfill gas. Evidence of this migration was detected in the drillholes to the east of the Stage I Landfill, and in the boreholes along its seaward boundary, where landfill gas was venting to the atmosphere via the seawall.

The investigations confirmed the requirement for landfill gas management to be undertaken at both sites. A multi-barrier approach was recommended, including positive landfill gas extraction to prevent excess pressure developing within the waste; the installation of perimeter barriers; and monitoring to assess the operational control of gas extraction and the effectiveness of the installed barriers in preventing migration. With these measures, occupation should not be affected in the proposed developments to the northwest and south of the Stage I Landfill, and the Stages II/III Landfill.

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