Construction on Former Landfills

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Abstract: Increasing demand for developable space in urban areas has created increased interest in construction on top of old landfills. Landfill redevelopment projects can include hard uses such as commercial, industrial, or infrastructure facilities and soft uses such as athletic fields, golf courses, and amphitheatres. Engineering challenges associated with landfill redevelopment include foundation design and landfill gas migration control. The large total and differential settlement often associated with landfills is an integral part of these challenges. Due to the large settlement potential, landfill redevelopment using shallow foundations is generally restricted to low-rise structures of one or two stories with raft foundations. Construction of taller structures using pile foundations is generally restricted to landfills without an engineered bottom liner system. Both deep and shallow foundations systems must be provided with protective measures against landfill gas migration. Despite the significant challenges associated with post-closure development on top of landfills, both hard and soft uses of old landfills are becoming increasingly common.

Keywords: Foundations, Gas, Landfills, Redevelopment, Settlement,

1. INTRODUCTION

Until recently, it was general practice to avoid closed and abandoned landfill sites. However, as developable space becomes scarce in urban areas, development on top of and adjacent to old landfills has become increasingly common. Sometimes, such development is driven by economic opportunity (cheap or well-located land), other times by necessity (the only available space or suitable location). Development of old landfills includes both hard and soft uses. Hard uses include building, roadway, and infrastructure development. Figure 1 depicts a retail store built on top of an old landfill south of San Francisco, California. Soft uses include golf courses, other recreational facilities (athletic fields), and amphitheatres. Figure 2 shows a golf course built on top of a landfill in Fullerton, California. The engineering challenges associated with development of old landfills include structural challenges such as foundation design and utility alignment and environmental challenges such as mitigation of explosion and health risks and air, soil, and groundwater impacts.

2. BACKGROUND

According to the Concise Oxford Dictionary, a landfill is defined as follows:

\textbf{Landfill, n.}
1. waste material etc. used to landscape or reclaim areas of ground.
2. the process of disposing of rubbish in this way.
3. an area filled in by this process.

For the purposes of this paper, the third definition is the operable one used herein. Landfills, in various forms, have been used for many years. The first recorded regulations to control municipal
waste were implemented during the Minoan civilization, which flourished in Crete (Greece) from 3000 to 1000 B.C. Solid wastes from the capital, Knossos, were placed in large pits and covered with layers of earth at intervals (Wilson, 1977). This basic method of landfilling has remained relatively unchanged right up to the present day.

Landfill design evolved as a series of responses to problems. Only when a problem was identified or reached a sufficient level of concern were corrective steps taken. These improvements were invariably driven by regulatory requirements. In Athens (Greece), by 500 B.C. it was required that garbage be disposed of at least 1.5 kilometres from the city walls. Each household was responsible for collecting its own waste and taking it to the disposal site. The first garbage collection service was established in the Roman Empire. People tossed their garbage into the streets, and it was shovelled into a horse drawn wagon by appointed garbageman who then took the garbage to an open pit, often centrally located in the community (Tammemagi, 1999). The semi-organised system of garbage collection lasted only as long as the Roman Empire. As industrialisation of nations occurred, many containment facilities were constructed to retain various types of raw materials and/or waste products. Most of these containment facilities were not designed and almost none were lined to prevent leakage of wastes into the surrounding environment.

Until the late 1970s there was little engineering input into landfilling practice and little consideration given to the impact of landfilled wastes on land and groundwater. By the end of the 1970’s, the problems in managing landfill sites had arisen from the contamination of soil and groundwater (with, for example, heavy metals, arsenic, pesticides, halogenated organic compounds and solvents) and the potential risks to exposed populations. From the 1970’s through the 1990s landfill design philosophy moved towards the objective of containment and isolation of wastes, which resulted in a major upsurge in the development of engineered waste disposal systems. In the United States and Europe, the evolution of municipal landfill design philosophy since the 1970’s has been relatively simple and has involved three significant phases through the 1990s and is entering a fourth phase as we enter the 21st century. These phases of municipal landfill development are summarized in Table 1. In Australia this evolutionary process has followed the same steps with the exception that the development of policy, regulation and guidance for landfill design was given more attention only in the mid-1990s (Bouazza and Parker, 1997). The focus in this decade is anticipated to be on mechanical and biological waste treatment, either in ground or prior to deposition, including increased use of leachate recirculation and bioreactor technology, as owners, regulators and engineers become more familiar with these concepts and their benefits with respect to decreasing long term costs and liabilities. While waste reduction and reuse efforts may diminish the per capita quantity of waste generated in industrialized nations, there is no doubt that
landfills will remain an important method of waste disposal for the foreseeable future due to their simplicity and cost-effectiveness.

Table 1 Summary of municipal landfill evolution (modified from Tammemagi, 1999).

<table>
<thead>
<tr>
<th>Date</th>
<th>Development</th>
<th>Problems</th>
<th>Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970s</td>
<td>Sanitary landfills</td>
<td>Health/nuisance, i.e. odour, fires, litter</td>
<td>Daily cover, better compaction, engineered approach to containment</td>
</tr>
<tr>
<td>Late 1980s-early 1990s</td>
<td>Engineered landfills, re-cycling</td>
<td>Ground and groundwater contamination</td>
<td>Engineered liners, covers, leachate and gas collection systems, increasing regulation, financial assurance</td>
</tr>
<tr>
<td>Late 1980’s, 1990s</td>
<td>Improved siting and containment, waste diversion and re-use</td>
<td>Stability, gas migration</td>
<td>Incorporation of technical, socio-political factors into siting process, development of new lining materials, new cover concepts, increased post-closure use</td>
</tr>
<tr>
<td>2000s</td>
<td>Improved waste treatment</td>
<td>?</td>
<td>Increasing emphasis on mechanical and biological waste pre-treatment, leachate recirculation and bioreactors</td>
</tr>
</tbody>
</table>

Construction on old landfills is a challenging task as the behaviour of waste is complex and difficult to characterize. Furthermore, many old landfills do not have engineered containment systems, and appropriate closure measures may not have been implemented. In addition, little is known about their content. It has been customary to avoid landfills whenever possible when planning the construction of highways, commercial, and residential and industrial facilities, and this is still the preferred approach. However, in recent years, as urban space becomes scarce, the development of old landfills has become increasingly common.

As landfills will remain an important method of waste control and as developable land becomes increasing scarce in urban areas, it is anticipated that construction on former landfills will become more common in the next decade.

3. LANDFILL COMPOSITION

Landfilled wastes include inert, municipal, and hazardous wastes. Inert waste includes construction and demolition debris, some types of contaminated soil, whole and shredded tyres, and asbestos. Inert waste landfills are perhaps the easiest type of landfill to redevelop as environmental problems are minimal and they can be improved and/or stabilized using conventional geotechnical ground improvement techniques. Therefore, we will not address inert waste landfills any further in this paper. Hazardous waste may include some types of contaminated soil, chemical process and refinery wastes, and other by-products of commercial and industrial processes. Hazardous waste landfills are perhaps the least common type of landfill subject to redevelopment because of environmental and health and safety concerns. The engineering challenges associated with redevelopment hazardous waste landfills are in some cases simpler than those associated with municipal landfills, as hazardous waste landfills may not be subject to the same degree of degradation-induced settlement or gas generation as municipal landfills. While there is a higher degree of toxicity associated with hazardous waste compared to municipal waste, with properly engineered containment systems hazardous waste landfills can be redeveloped even for recreational purposes (Collins, et al., 1998). As municipal solid waste landfills are the most common type of landfill, and as redevelopment of municipal solid waste landfill includes all of the engineering challenges associated with redevelopment of both inert and hazardous waste landfills, the balance of this paper will focus primarily on redevelopment of municipal solid waste landfills.
Municipal solid waste (MSW) is comprised of household and commercial refuse and includes paper, cardboard, glass, metal, plastics, textiles, green waste, food waste, and other putrescible organic waste. MSW is the most common type of waste and MSW landfills are the most common type of landfills. MSW typically comprises a very heterogeneous mass of material that varies widely between geographical locations, as shown in Table 2, reflecting different consumption patterns and social habits. Furthermore, as wastes are progressively minimized, recycled, re-used, processed, and recovered, the characteristics of MSW arriving at modern landfill changes over time. In addition to changes over time in the waste stream arriving at the landfill, MSW deposited in landfills change with time due to decomposition by a combination of chemical, physical, and biological processes. These processes are well documented in the literature (Christensen et al., 1992, Barlaz & Ham, 1993) and it is not intended to expand on this in the present paper. However, it is worth noting that these processes will produce liquid (leachate) and gaseous by-products (landfill gas). The composition and quantity of both leachate and landfill gas will vary with degradation stage. Both leachate and gas production may be important parameters, in addition to waste mechanical properties, to take into account in the redevelopment of landfill sites.

Table 2. Waste components as weight percentage for different cities (modified from Bouazza and Van Impe, 1998).

<table>
<thead>
<tr>
<th>Components</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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<tbody>
<tr>
<td>Metals</td>
<td>5.5</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>4</td>
<td>-</td>
<td>3.5</td>
</tr>
<tr>
<td>Paper, cardboard</td>
<td>27</td>
<td>12</td>
<td>30</td>
<td>35</td>
<td>10</td>
<td>31</td>
<td>9</td>
<td>19</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Plastics</td>
<td>11.5</td>
<td>5</td>
<td>10</td>
<td>8</td>
<td>3</td>
<td>9.5</td>
<td>4</td>
<td>7</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Leather, wood, rubber</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>33</td>
</tr>
<tr>
<td>Textiles</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Putrescible materials</td>
<td>32</td>
<td>74</td>
<td>48</td>
<td>40</td>
<td>61</td>
<td>28</td>
<td>45</td>
<td>59</td>
<td>59</td>
<td>34</td>
</tr>
<tr>
<td>Glass</td>
<td>4.5</td>
<td>4</td>
<td>-</td>
<td>6.5</td>
<td>1</td>
<td>9</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Others</td>
<td>12.5</td>
<td>2</td>
<td>7</td>
<td>-</td>
<td>14</td>
<td>11</td>
<td>33</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

1-Bakersfield, Southern California (USA), 2- Nairobi (Kenya), 3-Kuala Lumpur (Malaysia), 4- Caracas (Venezuela), 5- Istanbul (Turkey) 6- Geneva (Switzerland), 7- Dakar (Senegal), 8- Athens (Greece), 9-Moscow (Russia), 10- Lima (Peru).

4. LANDFILL CLOSURE AND REDEVELOPMENT

Once the permitted capacity of a landfill site has been reached, it is closed. Formal closure of a landfill often includes a post-closure plan to provide for the environmental monitoring and maintenance necessary to protect public health and the environment. The post closure plan generally also addresses post closure use of the site, though restricted access open space remains the most common type of site use specified in post closure plans. However, there is increasing awareness among owners, public officials, and the community that closed landfills are a potential resource because, due to their open land area, they may be put to beneficial use. Indeed one of the advantages of a landfill site is that, once it is completed, a sizable area of land becomes available for other purposes. However, post closure development of a landfill requires careful consideration of potential engineering and environmental problems. The major engineering limitations associated with redevelopment of closed landfills are the potential for large total and differential settlement, which can result in structural damage to buildings on the landfill and damage to the landfill cap, and low bearing capacity, which either limits post closure development to light weight low rise structures or requires the use of deep foundations. If deep foundations are used, there are additional engineering challenges associated with downdrag due to waste settlement and waste settling away from the structure. Environmental challenges related to post closure development are associated primarily with dealing with the hazards of landfill gas. The other environmental challenge associated with post closure development is the risk of waste by-product migration, either in soil, groundwater, or the atmosphere, due to post-closure development activities.
Landfill gas migration represents a major concern for the redevelopment of MSW landfills due to the risk of fire and explosion associated with methane and the health risks associated with some of the non-methanogenic organic constituents. Methods of controlling gas in modern landfills include the creation of physical and pneumatic barriers, passive venting systems, and active gas collection and treatment systems, both within the waste and under structures. The presence of these gas collection systems and engineered covers in a modern closed landfill can mitigate post closure development hazards due to landfill gas to some extent. However, additional protective measures may be required for post closure development, even for a modern landfill with a geomembrane cap and an active gas control system.

The extent of the limitations that the above engineering and environmental challenges place on post closure landfill development will depend on a variety of factors, including the composition of the waste, the age of the waste, the degree of waste compaction, the climate, and engineered containment systems at the landfill. In general, landfills with relatively young waste that have only recently been closed will show substantially more methane generation and continuing settlement than older, more mature landfills and thus will have substantially greater challenges associated with immediate reuse. While redevelopment for soft use (i.e., parks, golf courses, landscaping, etc.) may mitigate to some extent the challenges associated with foundation design and gas control, soft use is often associated with the introduction of additional moisture to the landfill (e.g., through irrigation systems). Addition of moisture can significantly enhance landfill gas generation and settlement rates, “reactivating” degradation in dormant or mature landfills, particularly in arid climates. However, for both soft and hard use (i.e., infrastructure, buildings, bridge abutments, etc.) uses, redevelopment of both young and mature landfills is feasible provided that enough background information has been gathered about the site, that a proper assessment of the potential problems has been made, and that redevelopment is managed properly.

Closed landfill sites have been used for a variety of post closure land uses. Projects have ranged from parks, recreational facilities (Cooper et al., 1997, Castelao et al. 1999, Kissida et al., 2001), commercial or industrial developments such as container storage facilities, office facilities, shopping centres (Hinkle et al., 1990, Gifford et al., 1990, Bote & Andersen, 1997, Rollin & Fournier, 2001), motorway embankments (Perelberg et al., 1987), elevated highways, piled roadways or expressways (Oteo & Sopena, 1993, Shimizu, 1997, Yang and Anandarajah, 1998), to high rise buildings (Hirata et al., 1995). The above projects have required engineered solutions for the construction of deep and shallow foundations, landfill gas migration control and protection systems, access roadways, and utility corridors. There are also examples of construction on medieval landfills (Bouazza & Wojnarowicz, 2000) which represent another type of challenge.

Until recently, very little consideration was given during design to the potential future use of the land following landfill closure. However, about 20 years ago, landfill regulations began requiring landfill owners to prepare post closure maintenance and monitoring plans that addressed, among other things, post closure use for the site. Initially, for simplicity in developing these plans, many owners would simply designate the site for use as secure open space following closure. However, as the financial benefits of post closure use become more apparent and as pressure from the community increases to put landfill space to productive use following closure, alternative post closure use scenarios are becoming more common. In Japan, where available space is very scarce, 67% of closed landfills have been reused for various projects (Shimizu, 1997), whereas in Finland, where there is less pressure to find developable space, 80% of the closed landfills do not have a defined post closure use (Saarela, 1997). Owners are now recognizing that some of the problems encountered in utilising closed landfills can be mitigated if the post closure use is taken into consideration during planning, design and operation of the landfill. In some parts of the European community, mechanical and biological pre-processing of waste is now widely endorsed not only as a means of reducing post closure environmental liabilities but also as a means of accelerating post closure development and enhancing post closure development potential.
5. WASTE SETTLEMENT

Waste settlement is an important factor in both hard and soft post-closure uses of landfills. For hard uses, waste settlement directly impacts design of shallow foundations and indirectly impacts deep foundation design through the downdrag it may impose on them. For soft uses, settlement affects drainage grades and grade-sensitive uses (e.g., athletic fields, greens for golf courses). Settlement also impacts design of site utilities, pavements, and other ancillary features of hard and soft site development. Both total and differential settlements of the waste mass are of engineering concern.

Both short-term and long-term settlement processes impact landfilled wastes. Short-term settlement is primarily attributable to mechanical settlement (e.g., settlement due to waste compression from overburden effects). Due to the high permeability and relatively dry nature of most landfills, the primary mechanical settlement of the waste is usually essentially complete before site closure. Reviews of landfill performance data indicate that primary mechanical compression typically takes 10 to 100 days to complete (Hinkle, 1990, Stulgis et al., 1995, Coumolos and Koryalos, 1999). For post-closure development, mechanical settlement is generally only of concern for shallow foundation systems placed on the surface of the waste mass.

The mechanical phase of waste settlement is followed by the so-called time dependent settlement phase (long term settlement). In landfills, time dependent settlement may be characterized by a substantial amount of settlement over an extended period of time. While some of this time dependent settlement may be related to mechanical secondary compression, most time dependent waste settlement is usually related to the biodegradation process, which may take years to reach completion. Specific degradation (and hence settlement) rates vary widely, depending upon characteristics of the landfill site and the MSW it contains, climate conditions, and operational considerations. The factors affecting the magnitude of long-term settlement are many and are influenced by each other (Edil et al., 1990). Environmental factors, such as moisture content and climatic conditions, appear to be a primary factor influencing the long-term settlement rate.

Large oedometer tests carried out by Kavazanjian et al. (1999) showed that moist waste specimens had more time dependent deformation that the dry specimens. More importantly, the mechanical secondary compression settlement rate measured in these tests in even the moist specimen was an order of magnitude less than the back calculated secondary compression rate from field measurements. Bowders, et al. (2000) monitored surface settlements of two closed cells (waste thickness approximately 18 m) in the city of Columbia, Missouri (USA). No appreciable settlement was recorded during 180 days, which coincided with an exceptionally dry period for the region. Visual examination of the waste during drilling for gas recovery well installation showed the waste to be exceptionally dry. Diaz et al. (1982) observed that landfills 23 m and 14 m deep, respectively, in an arid region (<6cm/year of rain) experienced very small settlements with magnitudes as low as 3% of the original MSW fill thickness three years after closure, whereas in a region of moderate rainfall a 6-m deep landfill experienced a settlement with magnitudes as large as 20% of the original MSW fill thickness after the first year of completion. These observations reinforce the fact that it is necessary that all factors governing settlement behaviour be assessed and their influence understood before any predictive model can be developed.

In the absence of a predictive model for waste settlement, it is essential to make field observations of waste settlement before construction of new facilities if long-term waste settlement is an important design consideration. At the present time, site specific field measurements represent the only rational means of quantifying the rate at which a landfill is undergoing long-term settlement. Cumulative long-term settlement can be related to the amount of decomposable (organic) material in the landfill. Oftentimes, the amount of decomposable material can be
estimated based upon waste receipts or waste disposal practices representative of the time and place of landfiling. However, in an older landfill, estimation of the amount of decomposable material is complicated by uncertainty as to how much degradation has already taken place. In the absence of quantitative information of the amount of decomposable material in the landfill, it is often assumed the post-closure long-term settlement will be between 15 to 20 percent of the waste mass thickness, based upon past experience. For an older landfill, this percentage may be subjectively adjusted based upon judgement as to how much degradation has already taken place.

Also of concern to the designer, in addition to total settlement, is the differential settlement and its impacts on foundations and utilities. Significant differential settlement should always be expected, irrespective of how uniform the refuse is initially placed, due to non-uniformity of waste composition and changing boundary conditions. Changes in boundary conditions can be caused by the topography of the landfill (example: side-slopes, irregular landfill bottom), composition and age of the waste (different biodegradation processes) and previous use of the site (if used for storage or stockpiling for example). As a practical matter, in many instances, differential settlement is often estimated as half the total settlement, or 7.5 to 10 percent of waste thickness at various points in the fill. The tolerance of the proposed development to both total and differential settlements should be evaluated.

If the total or differential settlements are too large, then soil improvement techniques may be used to reduce settlements and improve post closure performance. It should be recognized that the conventional mechanical ground improvement techniques (e.g., surcharging or dynamic compaction) may only delay the onset of long-term settlements, as they do not influence the amount of decomposable materials in the landfill. However, despite limitations with respect to reducing long-term degradation, ground improvement techniques have been used effectively to improve the waste characteristics before foundation design on a landfill. Older unlined or clay-lined landfills have been successfully densified by tamping, dynamic compaction, and the use of waste columns before building on top of them. The use of these techniques in the redevelopment of several old landfills is described by Van Impe & Bouazza (1996) and Brandl (1997). In the case of dynamic compaction, it has been shown that the enforced settlement depends on the age of the landfill. Young landfills show generally higher enforced settlement (an enforced settlement of 2.8 m-3.8 m, corresponding to 50% of landfill thickness, has been reported by Lewis and Langer, 1994), while older landfills tend to reach settlements similar to those encountered with soils; i.e 0.2m to 0.6m (Van Impe & Bouazza, 1996).

6. REDEVELOPMENT FOR HARD USE
6.1 Hard Use Redevelopment Issues

Redevelopment of old landfills for hard use requires designing and constructing foundations either embedded into or through the waste body or located at the landfill surface. Consequently, there is the necessity to quantify the settlement and bearing capacity of the landfill and to make sure that gas emissions are properly controlled so as to pose no significant risk of explosion or hazard to human health and safety. Eventually, an old landfill will achieve biochemical and structural stability. However, a substantial duration may be required to reach a degree of stability that is necessary to substantially mitigate the engineering and health and safety concerns associated with waste degradation. Some investigators have advocated delaying redevelopment until the waste mass has stabilized. For instance, Emberton and Parker (1987) proposed the following set of criteria that should be met before considering a landfill site for redevelopment purposes.

- the site should have been closed at least 10 years prior to redevelopment;
- the waste should be shallow with a depth of less than 10 m;
- the site should have a stable low water table;
- the landfill should not contain toxic or hazardous materials, particularly liquid wastes; and
• the development should be appropriate for the site conditions. Thus, expensive measures to prevent ingress of landfill gas may not be economically viable for a low cost development.

While the above criteria may be desirable attributes of a redevelopment site, experience has shown they are not exclusionary. The increasing value of developable open space in urban areas, socio-economic and political considerations, and improved engineering analysis and design have facilitated redevelopment of many sites that do not meet these criteria. In fact, experience indicates there are very few municipal landfill sites that cannot be redeveloped if proper consideration is given to engineering and health and safety risks.

6.2 Foundations

Foundation construction on reclaimed landfills is a challenging task since it requires considering unusual aspects related to the mechanics of wastes. Large total and differential settlements are usually the governing factors in the choice of the foundation types. Shallow foundation systems are generally preferred to support relatively light structures. Heavier structures will require deep foundations. However, deep foundations are generally restricted to older landfill without engineered bottom liner systems. Table 3 summarizes the relative advantages and disadvantages of deep and shallow foundations on landfills. A detailed overview on foundations in landfills is given by Phillips et al. (1993), Dunn (1995) and Bouazza and Seidel (1999).

Table 3. Relative advantages of foundation systems for post closure landfill redevelopment.

<table>
<thead>
<tr>
<th></th>
<th>DEEP FOUNDATIONS</th>
<th>SHALLOW FOUNDATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing Capacity</td>
<td>Excellent</td>
<td>Limited to Two Stories</td>
</tr>
<tr>
<td>Relative Settlement</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Differential Settlement</td>
<td>Excellent</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Building protection</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Maintenance</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

In assessing the bearing capacity of landfills, one has to keep in mind that the thickness and the strength of the cover system play a very important role in foundation support. If the soil cover is relatively thick, then it may provide substantial bearing capacity for shallow foundations. However, the soil cover may often be thin compared to the foundation size. In this case, the load for the foundation will be transferred through the cover and will develop its bearing resistance in the waste. Therefore, a bearing capacity analysis will require evaluation of the strength of the waste. However, experience has shown that, because of the ductile characteristics of MSW, large deformations are necessary to activate the bearing capacity of the waste, and it is difficult to design a structure that will allow such large deformations. Therefore, while total settlement must be considered with respect to utility connections and building access, differential settlement tends to govern the structural design of shallow foundations on waste. For this reason, raft foundations are typically employed rather than isolated footings on waste. In many cases, if the soil cover is thin, engineered fill is provided beneath the foundation to bridge over non-uniform settlements. Furthermore, as shown in Figure 3, the fill can be combined with geogrids or high-tensile geotextiles to create a composite material with a higher rigidity to support larger foundation loads.
Driven piles are the type of deep foundations most commonly used to support large structures constructed on old landfills. Piles are used to carry the structural loads to the bearing strata below the waste materials, where they are carried by friction or end bearing. The waste itself typically does not have enough strength and resistance to settlement to provide pile capacity. The most typically used pile type is precast/prestressed concrete piles. Steel H piles and steel pipe piles have been used, but serious consideration must be given to potential corrosion of the steel members. Coating of H-Piles and filling of pipe piles with concrete have been employed to mitigate corrosion concerns. One concern with driven piles is that they may drive waste beneath the bottom of the landfill, possibly into the groundwater. For this reason, conical or wedge-shaped driving tips are often used on the piles. Pre-drilling through the waste is generally avoided due to problems associated with handling and disposal of drill cuttings. As noted previously, the use of deep foundations is generally restricted to landfills without engineered bottom liners.

As discussed earlier, significant long-term settlement of the waste fill can often be expected over the life of a structure built on top of the landfill, even if the structure is supported on piles. As the pile-supporting structure itself will not settle with the waste, waste settlement will result in the waste fill settling away from the building, as shown in Figure 4. To mitigate the impact of the relative settlement on site utilities, the utilities are often “hung” from the building slab, as illustrated in Figure 5. Another effect of waste settlement on deep foundations is to induce downdrag loads on the piles. Downdrag or negative skin friction occurs when the settlement of the material surrounding the pile exceeds the downward movement of the pile shaft. It is known that small (<5 mm) movements of a soil around a pile can fully mobilise the negative skin friction. While it has been shown that high strains are required to mobilise MSW strength (Manassero, et al., 1997), large deformations may be expected in most landfills and there is ample evidence of downdrag on leachate risers in waste to indicate that downdrag on piles will occur.

Data to estimate the downdrag on piles due to settlement of waste are very scarce. Oweis & Khera (1998) suggested that the downdrag force may be about 10% of the weight of overlying waste fills. Waste shear strength can be used to estimate downdrag. Gifford, et al. (1990) evaluated downdrag based upon waste strength considerations and suggested that downdrag loads of 15 to 20% of the pile design capacity should be included to account for the high compressibility of the landfill. Knowledge of the lateral stress on the pile is required to evaluate downdrag using a frictional shear strength. Very recently, Landva et al (2000) presented the results of a preliminary investigation on the lateral earth pressure at rest (K₀) in waste materials. It was found that the value of K₀ decreased with an increasing amount of fibrous constituents (0.26 ≤ K₀ ≤ 0.40) and that the critical condition for K₀ (when K₀ is maximum) is the long-term state when decomposable fibres were no longer present. This work represents a first step towards a better quantification of lateral stresses in landfills and it is certainly an area which needs further investigation. Rinne, et al. (1994) reported
Figure 4. Waste fill settling away from a building. Figure 5. Utilities hung from building slab.

direct shear results on the interface between domestic waste and concrete indicating an interface friction strength value of 30 kPa. However, one has to be very cautious about the limitation of this type of test since it does not reproduce the real behaviour of waste in a landfill. Dunn (1995) recommended that field pullout tests be completed on a series of test piles to develop site specific shear strength values which can then be used to refine the downdrag analyses. He also suggested that it is desirable to instrument the piles driven as part of the testing program to allow measurement over time of the actual downdrag loads which develop in the piles.

There are several methods to mitigate the downdrag problem. Some of the methods that have been suggested in the literature include the use of friction reducing coatings on piles, use of double pile system, or pre-drilling with an oversize hole that is filled with bentonite slurry (Dunn, 1995). Coating piles with bitumen to reduce downdrag is often used in conventional soils. In materials such as MSW, Rinne et al. (1994) reported that the reduction of downdrag for bitumen-coated, pre-cast prestressed concrete piles was on the order of 30% to 40%. An important issue, which should not be overlooked when the bitumen option is used is the range of temperatures existing in the landfill. High temperatures (50° to 70° C) are often reported in landfills. However, landfill temperatures tend to decrease with time and, in a mature landfill, typically range between 20° to 40° C, depending on the nature of the waste and landfilling practice. If bitumen coating is to be considered, waste temperatures should be investigated thoroughly since the performance of the bitumen coating can be adversely affected by high temperatures.

The decomposition of the waste and the way it has been deposited can also induce horizontal movements inside the landfill. To date, very little attention has been given to the effect of a lateral load (inside the landfill) on the overall performance of pile foundations in landfills. Maertens and Bloemmen (1995) presented a case history related to the installation of precast prestressed concrete piles through a landfill. The pile length was around 17 m. The cross section of the piles ranged from 0.22 m x 0.22 m to 0.35 m x 0.35 m. During the installation, 25% of the piles broke and had to be replaced by additional piles. Two possible failure mechanisms were identified: 1) Large bending moment generated in the pile shaft due to deflection from obstructions in the waste; 2) accumulation of wastes such as plastic, metals, etc. at the tip inducing an uneven stress distribution below the pile tip. It is also possible that piles broke due to large tension stresses developed during easy driving conditions in low strength waste. This case history illustrates that a landfill should be regarded as a system with a large deformation potential that can produce both horizontal and vertical loads.
6.3 Gas Protection Measures to Buildings

Gases such as methane (CH\textsubscript{4}) and carbon dioxide (CO\textsubscript{2}) are produced in most landfill sites. These gases can migrate into buildings or confined spaces and may accumulate to explosive concentrations. Methane gas is explosive at concentrations above 5 to 15 % by volume in air; these are the lower and upper explosive limits respectively. If methane concentrations are greater than 15% it is not explosive, however when it migrates it will, at some locations, become diluted into the concentration range where it can explode. Landfill gases also carry low concentrations of non-methanogenic organic compounds (NMOCs). Some of these NMOCs are known to be carcinogenic in trace concentrations (e.g., benzene, vinyl chloride). Hence, there is serious health concerns associated with chronic exposure to even low levels of landfill gas.

The movement of gases in porous media occurs by two major transport mechanisms: advective flow and diffusive flow. In diffusive flow, gas moves in response to a concentration gradient. In advective flow, the gas moves in response to a gradient in total pressure. To equalize pressure, a mass of gas travels from a region of higher pressure to a lower one. In the context of landfills, the primary driving force for gas migration, especially through cover systems, is advective flow. Advective flow develops from pressure differentials due to both internal gas generation and natural fluctuations in atmospheric pressure (barometric pumping). Indeed, falling barometric pressures tend to draw gas out of the landfill, increasing the gas concentration near the surface layers.

A number of recent events have brought the hazards associated with landfill gas very much into public view. The best known of these were the Loscoe, U.K, (Williams & Aitkenhead, 1991); Skellingsted, Denmark, (Kjeldsen & Fisher, 1995) and Masserano, Italy (Jarre et al., 1997) incidents, which resulted in extensive property damage and loss of lives. The Loscoe explosion in the United Kingdom for example, took place after atmospheric pressure dropped by 29 mbars in approximately 7 hours. The same phenomenon caused the Skellingsted and Masserano explosions. Elevation of the leachate/water table and temperature gradients can also give rise to pressure differences and lead to gas migration.

The potential for a landfill to produce gas should not necessarily be a restriction on whether the site can be developed. There is a wide range of available gas protection methods to suit different types of developments, depending on the level of risk that can be tolerated. In Australia, there are no guidelines specifying measures to be taken to protect building structures in or around landfills. However, in California, regulations require a building protection system that includes a membrane barrier beneath the structure and an alarm system within the structure for facilities built within 300 m of a landfill. Elsewhere, and in the UK in particular, guidance documents have been produced following landfill gas related incidents. Table 4 provides a scope of the protection measures that can be taken to mitigate landfill gas problems in the UK. Referring to Table 4, it is important to stress that the monitoring of a gassing site should be carried out over a period of time and under varying weather conditions. In most of the cases presented by Wilson and Card (1999), ventilation of the underfloor subspace is the primary method of providing gas protection, with secondary protection provided by a barrier to gas migration above the subspace. An alarm system may also be placed inside the structure to warn occupants of gas accumulation. Figure 6 conceptually illustrates an advanced landfill gas building protection system. Probably the most important aspect in this type of construction measures is the long-term maintenance strategy plan put in place to guarantee their performance over a long period of time (i.e., until the landfill stops producing gas). Indeed whatever measure is selected must be able to protect the building structure for the useful life of the facility.
Figure 6. Potential landfill gas alternative protection system (Geosyntec Consultants patent pending).

Table 4: Scope of protection measures (modified from Wilson and Card, 1999).

<table>
<thead>
<tr>
<th>Limiting CH₄ con. (% by vol)</th>
<th>Limiting CO₂ con. (% by vol)</th>
<th>Limiting borehole gas volume of CH₄ or CO₂ (l/h)</th>
<th>Residential building</th>
<th>Office/commercial/industrial development</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.07</td>
<td>No special precautions</td>
<td>No special precautions</td>
</tr>
<tr>
<td>&lt; 1.0</td>
<td>&lt; 1.5</td>
<td>&lt; 0.7</td>
<td>Well constructed ground or suspended floor slab, geomembranes sealed around penetrations, passively underfloor sub-space and wall cavities</td>
<td>Reinforced cast in situ ground slab. All joints and penetrations sealed. Possibly geomembrane. Granular layer below slab passively vented to atmosphere with interleaved geocomposite strips or pipes</td>
</tr>
<tr>
<td>&lt; 5.0</td>
<td>&lt; 5.0</td>
<td>&lt; 3.5</td>
<td>Well constructed suspended or ground slab. Gas resistant geomembrane and passively ventilated underfloor sub-space</td>
<td>Reinforced concrete cast in-situ ground slab. All joints and penetrations sealed. Waterproof/gas resistant geomembrane and passively ventilated underfloor sub-space</td>
</tr>
<tr>
<td>&lt; 20</td>
<td>&lt; 20</td>
<td>&lt; 15</td>
<td>Well constructed suspended or ground slab. Gas resistant geomembrane and passively ventilated underfloor sub-space, oversite capping and in ground venting layer</td>
<td>Reinforced concrete cast in-situ ground slab. All joints and penetrations sealed. Gas resistant geomembrane and passively ventilated underfloor sub-space.</td>
</tr>
<tr>
<td>&lt; 20</td>
<td>&lt; 20</td>
<td>&lt; 70</td>
<td>Specific gas resistant geomembrane and ventilated underfloor void, oversite capping and in ground venting layer and in ground venting wells</td>
<td>Reinforced concrete cast in-situ ground slab. All joints and penetrations sealed. Gas resistant geomembrane and actively ventilated underfloor sub-space. In ground venting wells</td>
</tr>
<tr>
<td>&lt; 20</td>
<td>&lt; 20</td>
<td>&gt; 70</td>
<td>Not suitable unless gas regime is reduced first and quantitative assessment carried out to assess design of protection measures in conjunction with foundation design</td>
<td>Reinforced concrete cast in-situ ground slab. All joints and penetrations sealed. Gas resistant membrane and actively ventilated underfloor sub-space, with monitoring. In ground venting wells</td>
</tr>
</tbody>
</table>

Con. = concentration
7. REDEVELOPMENT FOR SOFT USE

The engineering issues associated with redevelopment for soft use are to some extent less challenging than those associated with hard use. Soft uses (e.g., parks, golf courses) generally involve outdoor open space. Hence, the potential for accumulation of explosive levels of landfill gases is less for soft uses than for hard uses. However, if gas is not properly controlled, it can still present explosion and health risks and may adversely affect the vegetation often associated with soft uses (e.g., turf grass). Therefore, gas migration control is still an important issue for soft use. Landfill settlement also remains a significant issue for soft use. Site utilities, paved areas, and foundations for ancillary facilities are all sensitive to large total and/or differential settlement. Furthermore, some soft uses may be even less tolerable of differential settlement than hard uses (e.g., athletic fields). Therefore, as in hard use, the impact of post-closure settlement must be carefully considered when planning a soft use project.

The most significant difference between soft use and hard use is that soft use frequently involves vegetation and irrigation. Particularly in arid and semi-arid climates, post-closure uses such as golf courses and athletic fields can require the addition of significant amounts of water to the top of the landfill for irrigation purposes. If the landfill cap does not provide appropriate infiltration resistance, increased infiltration may occur, leading to increased gas generation, settlement, and groundwater impacts. While a cover system can generally be engineered to provide sufficient infiltration resistance, the construction of a low-permeability cover (e.g., a geomembrane) on top of an inactive site can exacerbate both landfill gas migration at the perimeter of the cap and the landfill gas impacts to groundwater beneath the landfill. There are many instances where low-permeability cover construction has increased lateral gas migration and/or gas impacts to groundwater. Therefore, post-closure development for soft use requires consideration not only of infiltration and gas migration control through the top of the landfill, but also gas migration control at the perimeter of the cap and beneath the landfill.

As in post closure development for hard use, post-development maintenance and monitoring is an important consideration for soft uses. Annual inspections to detect and remediate damage to the landfill cover system, including the barrier layer, the gas control system, and the surface water control system, and to restore grades and repair utilities impacted by settlement must be provided for. Gas migration and groundwater monitoring are also key elements of the post-closure plan. Monitoring data and annual inspection reports should be reviewed by qualified engineers to determine if the landfill cover is performing as designed and if preventative or corrective actions are required.

8. CASE STUDIES

8.1 Tecnoparc de Montreal, Canada (Rollin & Fournier, 2001)

Movies studios, storage facilities, and administrative buildings were constructed on a landfill site that was active from 1870s until the 1960s. The site has fairly stabilised, very low concentrations of landfill gas were detected in 41 boreholes: CH₄ (0 to >50,000 ppm); SO₂ and H₂S <0.25-3.0 ppm); and CO <0.25-111 ppm). Five buildings covering a total area of 10,312 m² were built on piles and a geomembrane was installed on a collection and evacuation granular layer consisting of 150 mm diameter drainage pipes embedded in a 500 mm thick layer of 20-40 mm diameter material. A vacuum pump (100 cfm) was installed on the roofs of each building to continuously vent biogas contaminated air (Figure 7). A prefabricated bituminous geomembrane was selected to act as gas barrier due to the fact that it was easy to install (a large number of protruding elements, 367 piles, 187 pipes, 838 structural steel rods, as well as many sump pits, needed to be safely sealed), and attach to concrete structures (the geomembrane was mechanically attached to 1,032 metres of peripheral concrete walls). For safety purposes, 37 methane detectors were also installed
in different locations of the buildings. After one year of monitoring, no methane had been detected in the five buildings.

Figure 7 Remedial system under a building.

8.2 Redwood City Office Park, California

Miller and Vogt (1999) discussed the construction of an office park in Redwood City, California, USA, where the major design element was the installation of friction piles to support a 20-building complex. 40 m long pre-cast concrete piles were driven through an old landfill into the underlying soils over a one year construction period. 110 piles were installed for each building foundation, a total of 2,200 piles were installed for the whole complex.

8.3 Gaffey Street Landfill, Wilmington, California

Evans, et al. (2000) describe redevelopment of an inactive landfill in the Wilmington section of the City of Los Angeles, USA, as athletic fields. One of the primary redevelopment concerns was that the irrigation associated with post closure use would significantly increase infiltration to the waste, resulting in increased gas production, settlement, and groundwater impacts. The combined irrigation and rainfall necessary to sustain healthy turf grass in the semi-arid Los Angeles climate is approximately 140 cm per year compared to the mean annual rainfall of approximately 32 cm. Detailed water balance analyses were conducted using an unsaturated flow model to design an appropriate soil cover for the site. Results of the water balance analyses indicated that a monolithic evapotranspirative cover could not provide adequate resistance to infiltration. However, a capillary break cover could provide sufficient infiltration resistance provided that the irrigation system was properly controlled (i.e., the turf was not over-watered). In addition to inhibiting infiltration, the capillary break also provided a means for collecting and venting or treating (as necessary) landfill gas. To mitigate the potential for overwatering, landfill redevelopment included a “smart” irrigation system in which the irrigation controller was connected to a flow meter, a self tipping rain bucket, and an evapotranspiration gauge. Daily irrigation values are automatically calculated based upon precipitation and evapotranspiration over the previous 24 hours. The flow meter also has the capability of sensing line breaks in the irrigation system. Post-closure monitoring also includes neutron probe soil moisture sensors within and beneath the cap to evaluate the effectiveness of the smart irrigation system.

Non-vegetated areas of the landfill (e.g., roadways, parking lots, basketball courts) were capped with an asphaltic concrete low-permeability barrier layer. The asphaltic concrete included a
resin-impregnated fabric interlayer to inhibit cracking. The post-closure maintenance plan includes annual sealing of cracks in the asphaltic concrete and quarterly evaluation of the soil moisture probe data.

8.4 McColl Superfund Site, Fullerton, California (Collins, et al., 1998)

The McColl Superfund Site in Fullerton, California, provides an example of a hazardous waste landfill redeveloped for productive use (Figure 8 and 9). This 8.8-ha site contained 12 unlined pits containing highly acidic petroleum waste sludge (pH less than 1.0). While some parts of the site were closed as vegetated open space, some areas were redeveloped as a golf course. The cap in both the open space and golf course areas included a composite geomembrane/geosynthetic clay liner infiltration barrier. Due to the low bearing capacity of the waste, the foundation layer beneath the cap in the golf course areas included two layers of geogrid reinforcement (Hendricker, et al., 1998). The foundation layer also included gas extraction pipes connected to a blower and an activated carbon treatment unit. The cap was tied into a soil-bentonite slurry wall that completely encircled the site.

Figure 8 McColl Site (Circa 1995) with Sump Boundaries.  Figure 9. McColl Site in 1998 As Part of Los Coyotes Country Club.

5. CONCLUSIONS

Post-closure development of landfills includes both hard uses such as commercial, industrial, and infrastructure facilities and soft uses such as golf courses and athletic fields. Post-closure development of old landfills includes a variety of engineering challenges. These challenges include accommodating the large total and differential settlements typically associated with landfills and controlling the migration of landfill gas. Post-closure total settlement can approach 20 percent of the waste thickness, with differential settlement up to half that value. Shallow foundation systems for construction on top of landfills are typically limited to relatively light structures one or two stories tall, due to settlement considerations. Deep foundations bearing on firm strata beneath the waste may be used to support heavier structures. However, deep foundation systems are generally limited to landfills that do not have engineered bottom liner systems. Even though buildings on deep foundations may not settle significantly, the design engineer must still accommodate the relative settlement between the landfill and the structure. Both deep and shallow foundation systems require engineered systems to control landfill gas migration. These building protection
systems typically include a membrane barrier beneath the slab, a venting system beneath the barrier to minimize the build-up of gases beneath the barrier, and an alarm system within the structure.

Despite the substantial engineering challenges associated with building on old landfills, an increasing number of such projects have been successfully completed. Case histories describe the successful application of engineering principles to accommodate these challenges for both hard and soft post closure uses.

REFERENCES


