SUSTAINABLE DEVELOPMENT OF FORMER LANDFILL SITES: THE HONG KONG EXPERIENCE

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ABSTRACT

The term "sustainable development" was first coined by the Brundtland Commission in their *Report of the World Commission on Environment and Development* (1987) as "to meet the needs of the present without compromising the ability of future generations to meet their own needs." Landfill is one of the major methods in disposing waste in Hong Kong. However, besides the potential environmental nuisance during dumping of waste and the leachate problems, there are a number of drawbacks in employing landfill to dispose waste, including the loss of valuable land for landfill. There are now 13 closed landfill sites with a total plan area about 300 hectares in Hong Kong, and a restoration programme has been launched since 1999 to transform the closed landfill sites back into green or recreational zones for the use of future generations, fulfilling our obligations in sustainable development. This paper presents the afteruse development of two former landfill sites – Ngau Chi Wan and Jordan Valley Landfills – after their aftercare period (the development of the former landfill site having been awarded the Asian Urban Landscape Award 2010 by the United Nations HABITAT Regional Office for Asia and the Pacific). These landfill sites have now been restored to public parks with lawn area, archery field, model car racing unit, green house and education centre. This paper will describe the trail that demonstrates the process of the planning, design and construction of the public parks with considerations of environmental issues of landfill gas and leachate, and structural and geotechnical engineering issues to cater for the characteristics of the waste, and will also illustrate the potential problems due to ground settlement and means of solution.

Keywords: Sustainable development; Afteruse development of former landfills; Environmental, geotechnical and structural considerations in landfill afteruse development; Ngau Chi Wan Landfill, Jordan Valley Landfill

SUSTAINABLE DEVELOPMENT OF FORMER LANDFILL SITES:

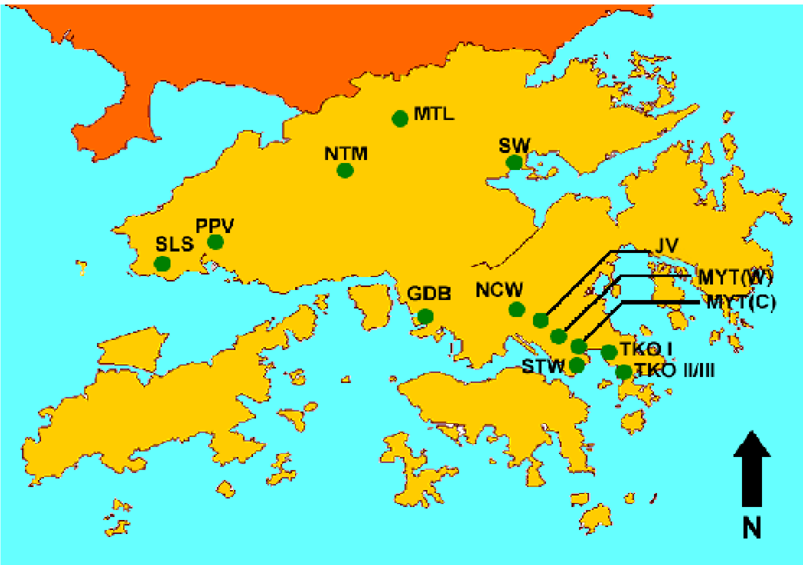
THE HONG KONG EXPERIENCE

INTRODUCTION

Landfill is one of the major methods in disposing waste in Hong Kong. In 2009, more than 3.27 million tonnes of waste were dumped in the various landfill sites in Hong Kong (*The Standard*, 4 October 2010). However, besides the potential environmental nuisance during dumping of waste and the leachate problems, there are a number of drawbacks in employing landfill to dispose waste, including the loss of valuable land for landfill. Both legislators and the community had expressed strong reservation on the further expansion of landfill sites (*The Standard*, 4 October 2010). On the other hand, there are now 13 closed landfill sites (total area of about 300 hectares) in Hong Kong (**Figure 1**), and a restoration programme has already been launched since 1999 to transform the closed landfill sites back into green zones for the use of future generations. In Hong Kong, once a landfill site is closed, the Environmental Protection Department ("EPD") will monitor the leachate and landfill gas emission and this period lasting for 20 – 30 years is called "aftercare" period. The main purposes of aftercare period are to ensure that the sites would not cause adverse environmental impacts to the environment and are safe for the "afteruse" development. During the late stage of aftercare period, afteruse development compatible with the ongoing aftercare work will be considered by EPD. As the continuing decomposition of waste results in the differential settlement process, excessive loading or massive building structures are to be avoided at this stage. Hence, most initial afteruse development will be restricted to recreational purposes. The BEAM standards *(available: http://www.hk-beam.org.hk/)* operated by the Building Environmental Assessment Method Society (the "BEAM Society"), which award Green Label to new or refurbished building projects, are now widely employed for assessment, performance improvement, certification and labelling of the environmental performance of construction projects in Hong Kong. The Green Label is rated in "Platinum/Gold/Silver/Bronze"; scores being given to different environmental aspects such as selection of site, location, material use and energy efficiency adopted in a project. Due to shortage of land for development in Hong Kong, credit is awarded to the use of contaminated land and landfill sites, provided that appropriate steps are taken to reduce environmental and health hazards to users and to neighbours. However, afteruse development on closed landfill sites requires careful planning and design to account for the characteristics of the waste as well as health and safety issues. The paper shares experience on the planning, design, construction and maintenance, and the ground settlement prediction for the afteruse development.

Project Brief

Out of the 13 closed landfill sites, the Architectural Services Department of the Hong Kong SAR Government was responsible for the restoration of Ngau Chi Wan ("NCW Landfill") and Jordan Valley ("Jordan Valley Landfill") closed landfill sites to recreational areas which have been opened to the public in mid-2010. The following paragraphs will briefly describe the history and the project briefs of both sites.



GDB : Gin Drinkers Bay
PPV : Pillar Point Valley
JV : Jordan Valley
SLS : Siu Lang Shui
MTL : Ma Tso Lung
STW : Sai Tso Wan
MYT(C) : Ma Yau Tong(Central)
SW : Shuen Wan
MYT(W) : Ma Yau Tong(West)
NCW : Ngau Chi Wan
NTM : Ngau Tam Mei
TKOI/II/III : Tseung Kwan O Stage I/II/III

Figure 1 Location of closed landfills in Hong Kong
(*Source*: EPD)

Landfilling operation at NCW Landfill commenced in 1976 and ceased in 1977. The site is a valley type landfill located to the north of Choi Wan Housing Estate, East Kowloon, Hong Kong. The site area is approximately 8 hectares, consisting of two separate disposal areas that have been used to form a series of platforms. A small additional area, that does not contain landfilled waste, is to provide access to a leachate/groundwater collection point. The site has now been developed into an archery field, children playground, and lawn and basketball courts. **Photo 1** shows the aerial view of NCW Landfill after the restoration. The afteruse development in NCW Landfill has just been awarded the Asian Urban Landscape Award in September 2010 by the United Nations HABITAT Regional Office for Asia and the Pacific. Landfilling operation at Jordan Valley Landfill commenced in 1986 and ceased in 1990. The site is located at New Clear

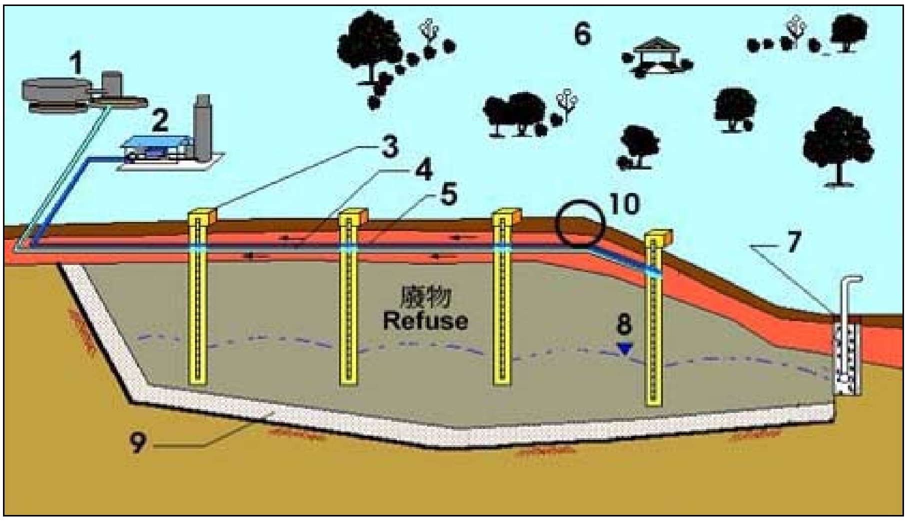
Water Bay Road, East Kowloon, Hong Kong. The site area is approximately 6.4 hectares and has now been restored to a model car racing circuit with single storey audience seat, toilet, green house and education centre. **Photo 2** shows the aerial view of Jordan Valley Landfill after the restoration.

Photo 1 Aerial view of NCW Landfill

Photo 2 Aerial view of Jordan Valley Landfill

Typical Restoration Works by EPD

Figure 2 shows the typical restoration works that are/have been carried out by EPD to reduce the potential safety and health risks of the closed landfills and to enable them for future afteruse development.



1. Leachate treatment plant
2. Landfill gas flaring / utilization plant
3. Leachate / gas extraction
4. Leachate header
5. Gas header
6. Recreational Uses
7. Gas venting trench
8. Leachate level
9. Drainage layer
10. Capping system

Figure 2 Typical cross section of restored landfill

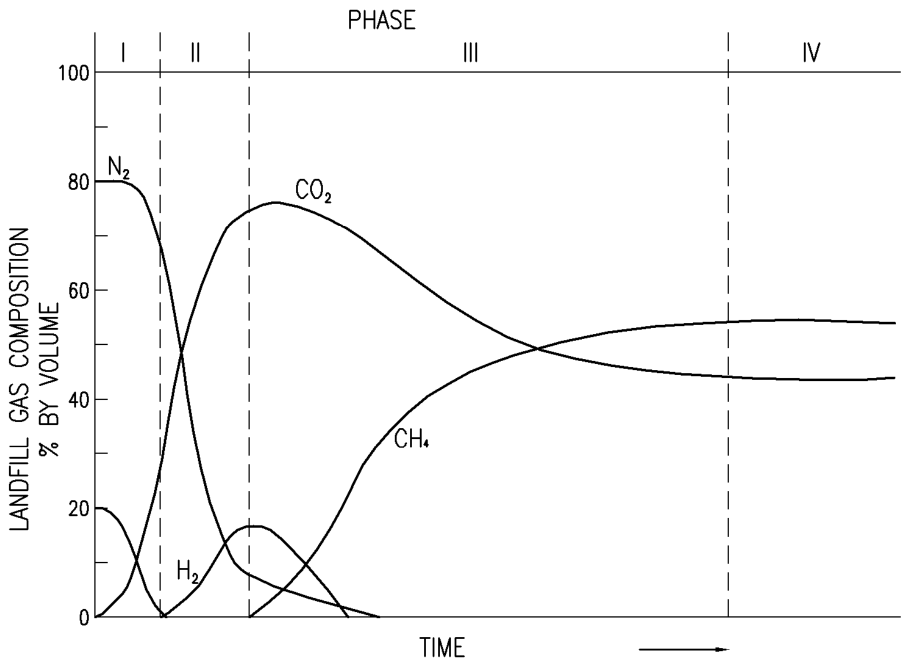
(*Source*: EPD)

The landfills are usually capped with geotextile polyethylene liner, overlaid by synthetic geo-composite drainage layer and the soil as cover layer to promote vegetation growth. A leachate management system including pumping wells is installed. Collected leachate is treated on site by leachate treatment plant prior to disposal at adjacent public sewers. Regular monitoring of landfill gas, leachate, organic emission, surface water, underground water, dust and odour etc. are carried out by EPD during aftercare period.

GAS AND LEACHATE MIGRATION AND CONTROL

Landfill Gas

Generally in a mature landfill site (over 2 years since infilling) gas is generated typically in proportions, 50 – 60% of methane (CH_4) by volume, with the rest being mainly carbon dioxide (CO_2) and a trace amount of nitrogen, hydrogen, ammonia, sulphur dioxide and carbon monoxide which are generated by the decay of organic materials. Since the rate of decomposition decreases with time after site closure, the composition of landfill gas will also change with time (**Figure 3**). Methane gas production and migration through the ground represent both a health hazard and fire explosion risk. Control limits of gas being detected are usually set at a level 0.5 – 1% by volume of methane (EPD 1997).



Notes: In general, Phase I will occupy a few days, Phase II a few weeks, Phase III about 1-2 years, while Phase IV can last some tens of years.

Figure 3 Landfill Gas Generation Pattern

(*Source*: Faruhar and Rover 1973)

For safety and health reasons, a landfill gas management system is therefore in place for a restored landfill site. Landfill gas is collected *via* either active gas extraction system or passive venting system, and in some landfill sites is converted to renewable energy. The most extensive use of such landfill gas is that in Shuen Wan Landfill site, which is located near to the Tai Po Gas Plant, and hence the landfill gas is collected by 1.3km of pipelines to the Towngas (Tai Po) Production Plant producing about 130,000 MJ/day as heating fuel substituting for the fossil fuel naphtha and reducing the emission of some 2,500 tonnes of carbon dioxide every year according to the information given by EPD. The principle of the passive venting system is to lay perforated pipes to collect landfill gas, followed by a venting system to provide a low-pressure pathway for landfill gas flow. Landfill gas generation causes the subsurface pressure of the landfill to increase and flow toward lower pressure zones created by the landfill gas collectors. The extraction of landfill gas is achieved by solar powered fans (**Photo 3**) to increase the flow and decrease the pressure within the piping network. Passive vents are provided over the whole site for the landfill gas emission (**Photo 4**). Active gas collection systems include vacuum pumps to move gas out of the landfill. Vacuum creates a low pressure migration pathway for the landfill gas to the well for collection. In NCW Landfill, passive venting system was adopted, whilst active gas extraction was adopted in Jordan Valley Landfill.

Photo 3 Solar Power Fan for Landfill Gas Venting System

Photo 4 Landfill Gas Passive Vent Riser

Leachate Control

Leachate is another environmental concern in a landfill site, and is generated mainly by the infiltrated water, which passes through the solid waste fill and facilitates transfer of contaminants from solid phase to liquid phase (Farquhar 1989). Due to the inhomogeneous nature of the waste and because of the differing compaction densities, water percolates through and appears as leachate at the base of the site. Leachate contains high concentrations of contaminants, such as ammoniacal nitrogen, heavy metals and organic compounds, and it would affect both surface and groundwater resources (Yim 1989, Farquhar 1989). Yim (1989) measured the composition of the leachate from various landfill sites in Hong Kong between 1977 and 1984 (**Table 1**), and its comparison against those in the US is also shown alongside with the data.

Table 1 Leachate Composition in Hong Kong

Constituent		Controlled Tips in Hong Kong: Sai Tao Wan	Ngau Chi Wan	Ma Yau Tong (West)	Ma Yau Tong (Central)	Pillar Point Valley	Controlled Tips in U.S.A.
pH	Max	8.5	8.5	8.5	8.3	8.9	8.5
	Average	7.8	7.9	7.8	7.8	8.1	6.0
	Min	6.2	6.8	6.9	7.2	6.7	5.3
BOD_5 (Biochemical Oxygen Demand)	Max	7300	3700	6400	22000	4800	30000
	Average	1043	456	831	1878	2470	10000
	Min	95	22	37	73	180	2000
COD (Chemical Oxygen Demand)	Max	46000	33000	14000	29000	30000	45000
	Average	4986	2459	2595	4072	14450	18000
	Min	520	259	490	910	3200	3000
SS (Suspended Solids)	Max	6900	7700	860	1100	25000	1000
	Average	383	863	139	197	8559	500
	Min	13	34	8	16	88	200
AN (Ammonia Nitrogen)	Max	4600	2400	2100	3100	4200	800
	Average	1339	730	849	1549	2135	200
	Min	250	159	140	610	440	10
Cl (Chlorine)	Max	13000	6600	13000	NA	NA	3000
	Average	4382	2724	5463			500
	Min	570	490	3700			10
PO_4 (Phosphate)	Max	15.0	65.0	28.0	19.0	270	70
	Average	4.9	12.5	6.9	10.6	119	30
	Min	0.1	0.7	0.2	3.4	11	1
S (Sulphur)		≤ 0.1	≤ 0.1	≤ 0.1	≤ 0.1	≤ 0.1	NA
Conductivity	Max	28000	11000	28000	27000	NA	NA
	Average	19550	5490	11533	15318		
	Min	11000	1200	1100	9000		
Notes: All constituents are measured in mg/l, except pH and conductivity. Conductivity is measured in microhms/cm.							

(*Source*: Yim 1989, ASCE 1970)

EPD installs a leachate management system including pumping wells for a restored landfill. Leachate produced is collected by subsoil drains on top of the PVC membrane and connected to nearby sewer. Collected leachate is treated on site by leachate treatment plant prior to disposal at adjacent public sewers. PVC membrane liner and chunam liner were used, and typical arrangement of liner and sub-soil drains are shown in **Figure 4**.

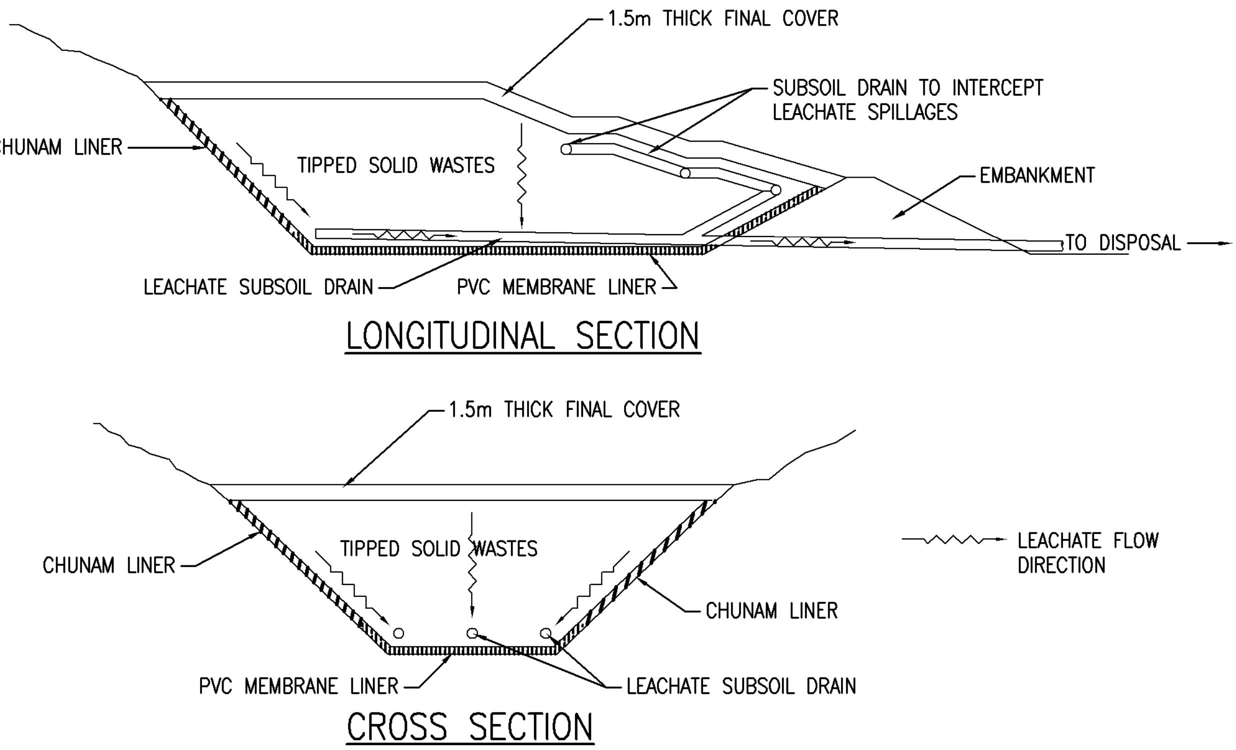


Figure 4 Leachate Collection System

PRE-REQUISITES FOR DEVELOPING CLOSED LANDFILL SITE FOR AFTERUSE

Careful planning, design and monitoring for the afteruse development are required before, during and after the construction to account for the characteristics of the waste as well as health and safety issues. The following are considered as pre-requisites before developing a closed landfill site.

Emission of Landfill Gas and Leachate

Data on leachate and landfill gas should be carefully analyzed before deciding to develop a landfill site. For NCW and Jordan Valley Landfills, the data on landfill gas and leachate from EPD are shown in **Table 2** and **3**. For Jordan Valley project, a methane level of 0.5% by volume was detected in November 2001, and other than this single data, all the monitoring results for NCW and Jordan Valley Landfills showed that the methane composition of the landfill gas and leachate volume were feasible for afteruse development.

Table 2 Methane content and leachate volume in NCW Landfill

Period	Methane (% by volume)	Leachate Volume
2004-2005	0	Low

(*Source*: Maunsell Environmental Management Consultants Ltd 2005)

Table 3 Methane content and leachate volume in Jordan Valley Landfill

Period	Methane (% by volume)	Leachate Volume (m^3/month)
2001-2002	0 (except 0.5% in November 2001)	2946

(*Source*: Maunsell in association with Urbis & RMJM 2003)

Slope Stability of Landfill Site

Several landfill slope failures occur infrequently outside Hong Kong, leading significant loss of life. Most notable accidents occur at Istanbul Landfill (1993) in Turkey, Rumpke Sanitary Lanfill (1996) in Ohio, US, Hiriya Landfill (1997) in Israel, and Payatas Landfill (2000) in Philippines. The issue of the stability of landfill slopes is, however, more complicated than that of ordinary fill slopes. The waste may contain materials harmful to health and environment and therefore, apart from direct risk to life in case of a large scale failure, any failure may also release harmful contaminants directly into the future development. Also, as the waste is made up of heterogeneous materials, the conventional strength tests cannot measure its shear strength parameters and its strength may further change with time (Huvaj-Sarihan and Stark 2008). In the stability analysis, the strength parameters are therefore usually estimated by some formulae or from past experience. Thus, it is imperative that confirmation of the landfill slope safety should be made before afteruse development of a landfill site.

Ground Settlement

Settlement is another major geotechnical aspect of the restoration and development of closed landfill sites. Landfill settlement will cause the following problems for afteruse development (Yim 1989):-

a) severe distortion and damage to buildings,

b) sagging of surface channels or ground resulting in water ponding,

c) reversed flow of underground drain if the fall is inadequate,

d) cracking of surface paving and surface channel causing infiltration of water into the refuse layer,

e) rupture of utility lines/ underground drains.

It should further be noted that settlements in landfill are both irregular and excessive. The maximum settlement depends mainly on the thickness of the waste which may not be necessary at the centre part of the platform. While the total settlement can be relatively easier to be handled, differential settlement is, however, a major concern, as it will induce building distress or crack leading to unserviceability of the building. It is therefore important to have a proper planning and building design for development on landfill sites.

Landfill Site Closure Period

It is necessary to ensure that the ground settlement is generally stabilized without excessive settlement. Research (**Table 4**) generally agrees that after 20 years closure the landfill would have settled by 15 to 50% of its thickness and that most settlement would have been completed by that time. As a rule of thumb, at least **20 years after closure** should therefore have elapsed before developing a closed landfill site for the afteruse development.

WASTE SETTLEMENT

Mechanism

The mechanism of waste settlement is complex, and the settlement can be attributed mainly to degradation and deformation of the waste within the landfill. Settlement is classified into two stages: primary and secondary settlement (**Figure 5**). Primary settlement further involves two phases: phase I represents immediate settlement induced by compression of waste components, and phase II represents slippage or reorientation of particles. However, primary settlement will be completed in around 4 months after site closure, and hence is not a main concern in afteruse development. Secondary settlement (phase III), on the other hand, will commence after primary settlement is completed, and involves the biochemical degradation of waste. **Table 4** summarizes the literature on the settlement behaviour of landfill, and the general consensus is that secondary settlement will mostly have been completed in around 20 years.

Table 4 Summary of Settlement Behaviour of Landfill

Source	Waste type	Settlement (% of depth of waste)	Time period (years)
Edgers et al (1992)	Municipal solid waste	25 - 50 %	20
Edil et al (1990)	Municipal solid waste	5 - 30%	Most occurs in 2 years
Frantzis (1981)	Household refuse	Up to 20	65% occurs in 3 years, most occurs in 15 years
Hurtric (1981)	Household refuse	Overall 15 - 20%	Around 20
Jessberger (1994)	Mixed landfill	About 20%	15 - 20
Nobel et al (1988)	Household refuse	20%	20
Sarsby (1987)	Household and commercial waste	6 - 9%	5

(*Source*: Sarsby 2000)

Settlement Curve

Bjarngaed and Edger (1990) provided typical settlement versus time curve for landfill (**Figure 5**). The settlement rapidly drops in first few months after site closure. The curve tends to be linear with log time when approaching to secondary settlement period. As stated above, for afteruse development secondary settlement is a major engineering concern, as the settlement during this phase is time-dependent.

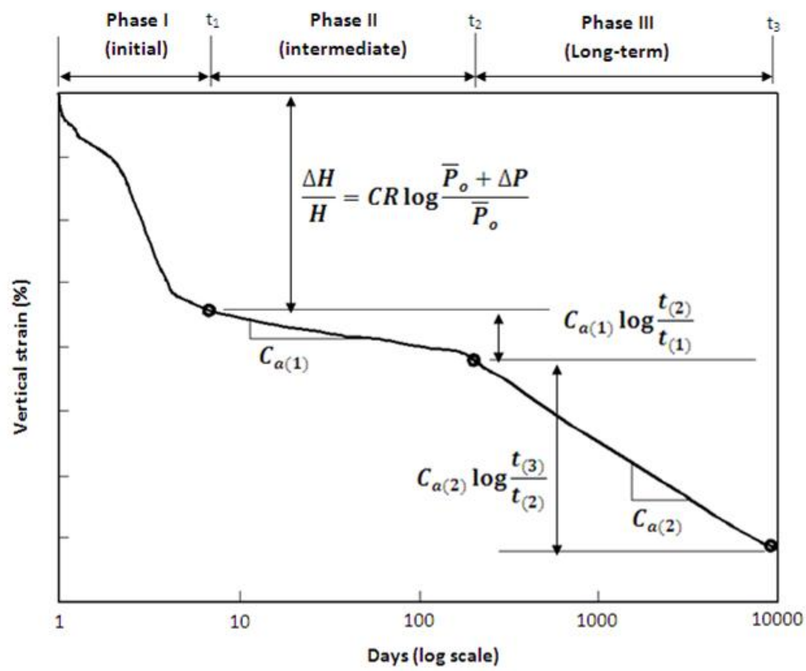


Figure 5 Typical settlement curve vs time for landfill

(*Source*: Bjarngaed and Edger 1990)

Table 5 summarizes the maximum ground settlements recorded before and during construction in NCW and Jordan Valley Landfills. **Figure 6** and **7** show the settlement curve at various settlement monitoring points recorded from EPD in both NCW and Jordan Valley Landfill between 1998 and 2010. The data recorded so far follow the trend as suggested by Bjarngaed and Edger (1990).

Table 5 Recorded Maximum Ground Settlement in NCW and Jordan Valley Landfills

Site	Year of Site Closure	Stage	Period	Maximum Settlement (mm)
Ngau Chi Wan	1977	Aftercare	2000 - 2008 (8 years)	396
		Construction	2008 - 2010 (2 years)	101
Jordan Valley	1990	Aftercare	1998 - 2008 (10 years)	833
		Construction	2008 - 2010 (2 years)	274

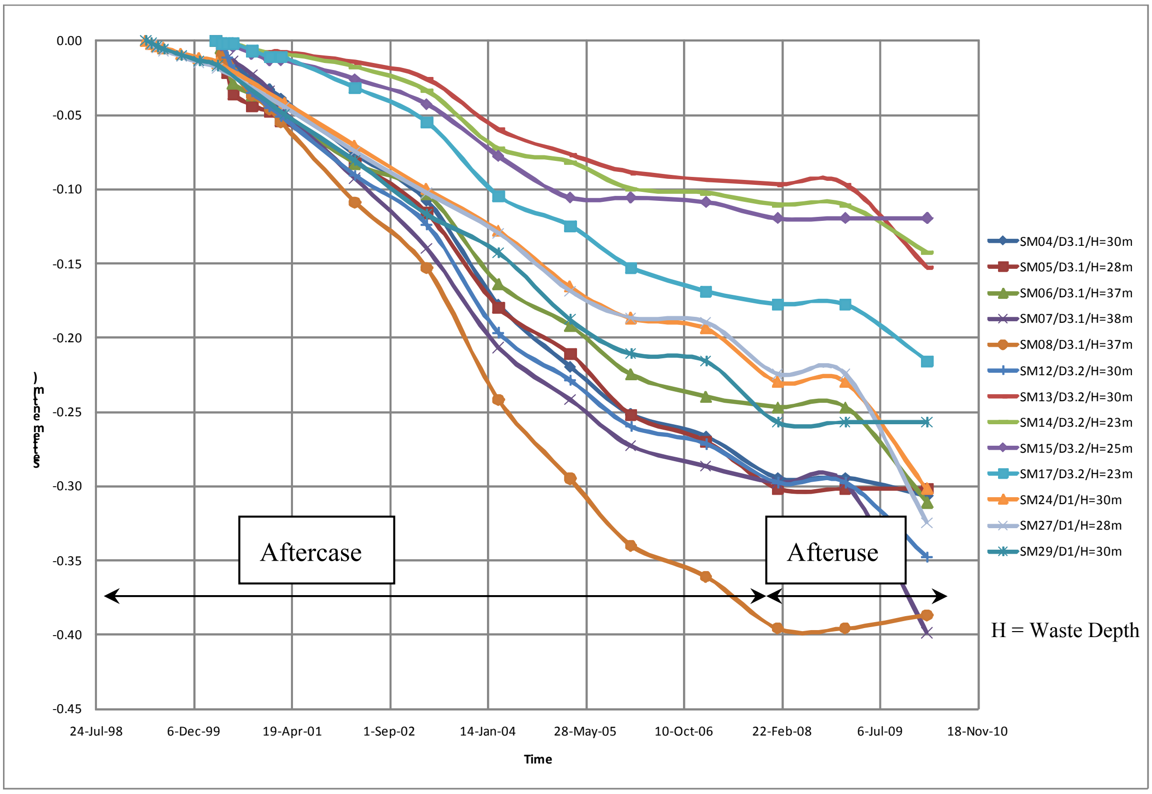


Figure 6 Recorded Ground Settlements in NCW (1998-2010)

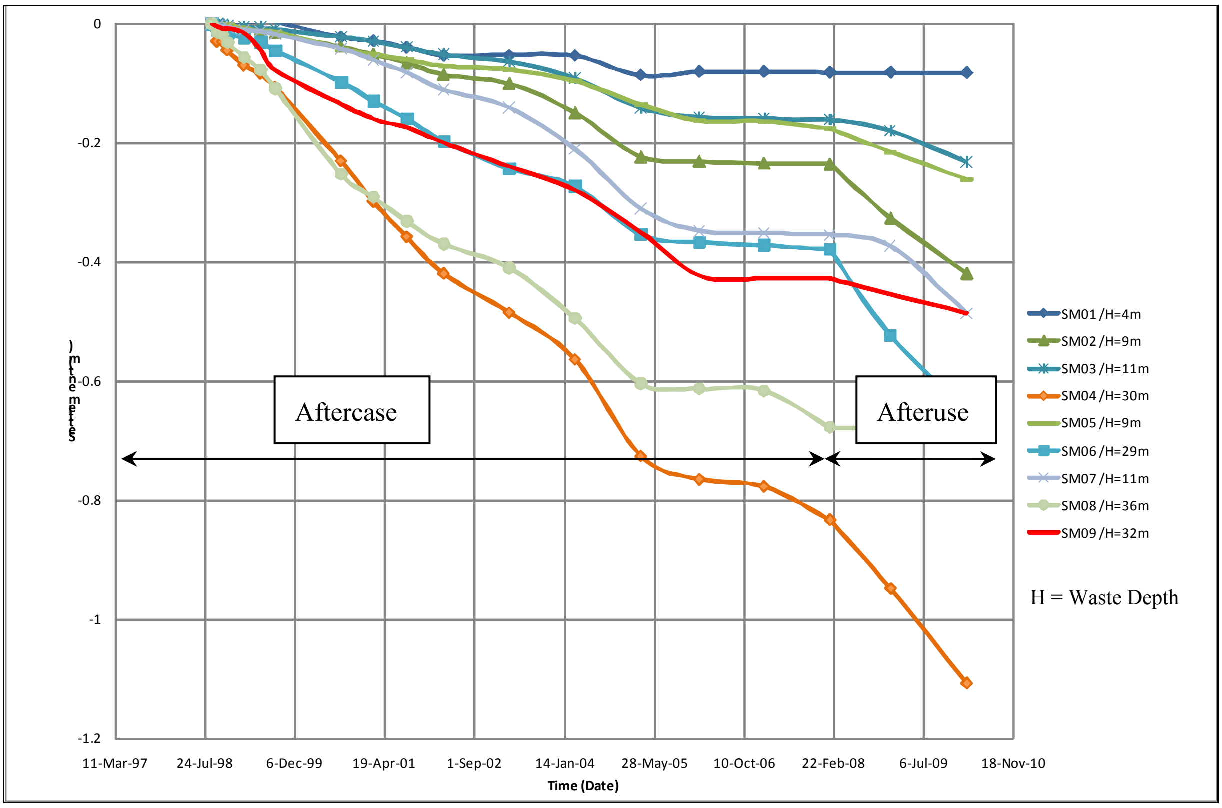


Figure 7 Recorded Ground Settlements in Jordan Valley (1998-2010)

Settlement Estimation

Ground settlement is mainly related to the waste thickness, rate of consolidation, creep of waste material and chemical/biological decay accompanied by gas/liquid production which in turn reduces the solid volume. Numerous settlement estimation methods (e.g. Gibson and Lo 1961, Edil et al 1990, Ling et al 1998, Sowers 1973) have been used to predict the landfill. **Table 6** summarizes the various methods to estimate the settlement of landfill.

Table 6 Summary of settlement estimation methods for landfill

Rheological Model (Gibson and Lo 1961) $\Delta H = H(\Delta p)\{a+b[1-\exp(-\lambda/b)t]\}$	where: H = initial thickness of waste; Δp = change in pressure; a = primary compression parameter; b = secondary compression parameter; λ/b = rate of secondary compression; and t = time since load application.
Power Creep Model (Edil et al 1990) $\Delta H = H\ \Delta p * m * (t/t_r)^n$	where: H = initial thickness of waste; Δp = change in pressure; m = reference compressibility; n = compression rate; tr = reference time; and t = time since load application.
Hyperbolic Function Model (Ling et al 1998) $S = t / (1/\rho_o + t/S_{ult})$	where t = time interval of interest; S = settlement occurring in time interval (t); ρ_0 = rate of settlement at the beginning of the time interval; and S_{ult} = ultimate settlement. The value of ρ_o and S_{ult} may be obtained through a regression analysis conducted on the *t/S* versus *t* relationship.
Sowers Model (Sowers 1973) Total Settlement = Hp + H_S H_p (Primary) = $H\ C_{ce} \log [(p_0+\Delta p)/p_0]$ H_S (Secondary)= $H_n\ C_\alpha \log(t_{n+1}/t_n)$	where: H = initial thickness of waste; H_n = thickness of waste at time t_n; $C_{ce} = C_c/(1+e_o)$; C_c = compression index; e_o = void ratio; C_α = secondary compression index; p_0 = initial overburden pressure; Δp = incremental pressure; t_n = reference time; t_{n+1} = time of interest.

The rheological model, the power creep model and the hyperbolic model do not require separation of settlement into primary and secondary components. Park et al (2007) note that the rheological model considerably underestimates the settlement; whilst the estimation is considerably overestimated for power creep model. The model proposed by Sowers (1973) is the most widely used approach for settlement prediction for landfill because of simplicity and familiarity. This approach considers primary and secondary consolidations separately. The primary settlement component is stress dependent, which occurs rather quickly in the first few months after the landfill is closed. Secondary settlement is the non-stress dependent long–term creeping settlement and can take place over many years. The Sowers' model further assumes that the portion of the settlement curve corresponding to secondary settlement is linear with respect to the logarithm of time as expressed in the above formula (Sowers, 1973). Using Sowers' model, the estimated maximum settlements in NCW and Jordan Valley Landfills are respectively to be 1.0m and 1.2m after 50 years, and occurred at the lawn area. Buildings have therefore been located at the areas with least waste depth, and the settlement is expected to be of 300mm after 50 years.

PLANNING, DESIGN, CONSTRUCTION AND MAINTENANCE OF AFTERUSE DEVELOPMENT

To achieve an acceptable performance as the site settles and to minimize future maintenance, the following have been employed in the design, planning and construction stages of the two afteruse development at NCW and Jordan Valley Landfills.

Environmental Impact Assessment and Gas Control

During the design stage, a landfill gas hazard assessment is required. During the construction phase, regular checking on the level of landfill gas has been carried out in trenches and other excavation. When the afteruse development has been opened to the public, the building blocks are being checked using portable gas detectors for the initial six months and an automatic gas detection system has also been installed to forewarn for any potential leakage of landfill gas.

Overall Planning and Layout of Buildings

Settlement of landfill is related to its thickness and waste deposition. The building structures have been located in location where the depth of landfill is thinner. The size of each building was limited to 20m in length or breadth in order to minimize the effect of differential settlement on the building. Of course, the buildings were of single storey, and be lightweight. As settlement and differential settlement will occur at landfill sites, facilities need to meet hard-surfaced or stringent level-ground requirements (e.g. basketball court, gateball court) have been avoided. Soccer pitch and other similar facilities were turfed using natural grass. Large and heavy utility and services structures such as the transformer and sewage pumping stations were located away from landfill, i.e. over natural ground. Also, trees were planted away from landfill areas, in order to avoid damage to the capping layers by the tree roots, and tree species with shallow root have been chosen.

Predicted Rate of Settlement and Design of Foundation

The major challenge in designing a landfill site is to predict ground settlement and to cater for the large differential settlement. Assessment of ground settlement for the overall site may help to select the ideal location for building structures. Estimation of differential settlement of building using the models discussed in the previous section has helped in structural analysis and design of the foundation and building structure. Cellular and/or rigid raft footings as foundation have been employed to minimize excessive differential settlement in the building structure.

Design of Building Fabrics and Structures

One of the major concerns for building design is to cater for differential settlement. The following structural solutions have been adopted:-

a) Structures were lightweight built with structural steel and of single storey. This arrangement can reduce the imposed load on the landfill. The design of steel frame structure with column fixed at footing and pinned joint connection for beam-column junction has been adopted to allow more flexible movement.

b) Rigid cellular and/or raft foundation has been used to minimize differential settlement.

c) No rigid construction for partitions or external walls was used.

d) To prevent the ingress of landfill gas into the building block, the ground floor was raised by 500mm above the ground surface, with the service entry points were located above ground for ventilation purpose (**Photo 5**).

(a) During construction

(b) After completion

Photo 5 Raised ground floor for venting of sub-slab gas

e) To allow for differential settlement, the plan size of each building block was limited to 20m, or the building block was split into separate portions and connected by transition slab (**Figure 8**).

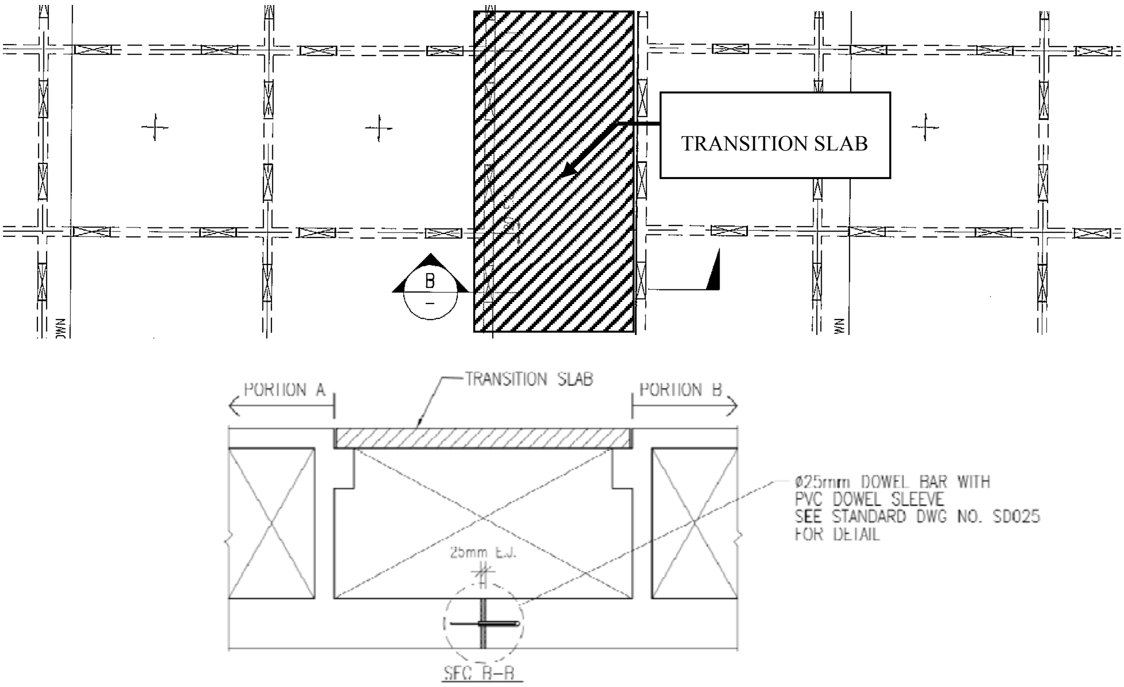


Figure 8 Transition slab details

Design of Utilities

All drain and fresh water pipes at the site were laid above ground (**Photo 6**) for ease of discovery of any crack or leakage for prompt rectification in order to prevent adverse effect to the underground leachate management system. If ground installation is inevitable, the services were installed within a concrete trough (**Photo 7**). The concrete trough can also eliminate the effect of differential settlement on the pipes. Flexible joints allow for all piping works including drainage, water supply and E&M cables. Utility companies were advised of the possible presence of landfill gas in the subsurface, and this has been taken into account in the design, construction and maintenance of their works. The voids around any service ducts, drainage pipes or cables within conduits were filled with gas resistant mastic. Dense well-compacted concrete was used for the drainage manholes to resist gas permeation; otherwise HDPE membrane was employed to wrap the manholes. Vent pipes were also provided to allow any gases to dissipate harmlessly to atmosphere. Soak-away water discharge to the underground was not allowed as water discharge may rise up the leachate level.

Photo 6 Utilities laid above ground

Photo 7 Utilities located within trough

Design of Pavement

Tarmac (flexible pavement) is not recommended because of substantial settlement of the landfill with time. By contrast, cracks will easily form in hard paving due to differential settlement. Paving was therefore made of concrete block (**Photo 8**) for easy repair after damage or unevenness was observed due to settlement. Improvement was made by providing movement joints in say 6m to 8m c/c in both directions.

Photo 8 Pavement with concrete blocks

Settlement Monitoring during Construction and after Handover

Settlement monitoring on ground, platforms, buildings and utilities was carried out during construction, and still continues after the open of the recreation grounds to the public. Review on overall settlement analysis using the measured data has been carried out if significant settlement is noted.

Construction

As no excavation is allowed in landfill site to avoid damage to the capping system, this will impose constraint on the construction works, as foundation works inevitably involve excavation. The solution adopted in NCW Landfill and Jordan Valley Landfill is to place the raft foundation on top of the landfill without excavation and then raise the levels of the platform to bury the foundations. Depending on the level of methane in the landfill gas, it is sometimes suggested that no welding should be permitted, unless the working area is continuously monitored for methane contents. Sparks are prevented from reaching combustible gases, and working procedures should be in place before commencement of works. Besides, smoking and naked flames are strictly prohibited.

Project Completion and Maintenance

Before the project completion, the designer was required to prepare maintenance manuals to the client summarizing the inspection and maintenance work covering the platforms, man-made slopes and retaining structures formed to be carried out. The maintenance manual shall also contain specification, procedures and advice for future maintenance use. In view of the continuous settlement during afteruse period, monthly visit by technical staff and quarterly inspection by engineer to keep track of ground, building settlement and building condition have also been carried out. Therefore, the annual maintenance cost of afteruse development on landfill sites will be higher than that in other projects.

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