Afteruse development of former landfill sites in Hong Kong


Architectural Services Department, HKSAR Government, Hong Kong, China

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A B S T R A C T

Landfill is one of the major methods in disposing of municipal solid waste (MSW) in Hong Kong. There are now 13 closed landfill sites in Hong Kong, and a restoration program has been launched since 1999 to transform the closed landfill sites back into recreational area. The MSW underneath these closed landfill sites will biodegrade slowly and gradually, releasing toxic gases and leachate. As there have only been a few afteruse development ever completed in Hong Kong, this paper describes the consideration in planning and design of two former landfill sites in Hong Kong – Ngau Chi Wan (NCW) and Jordan Valley (JV) landfills, in particular a discussion on the MSW settlement. Various models in predicting the long-term MSW settlement have been available. This paper reviews the applicability of these models to predict MSW settlement. However, as the predicted settlements can be significantly in error, they need site-specific calibration and validation. This paper therefore presents the settlement monitoring data in these former landfill sites over the last 30 years, and suggests modifying the Bjarrgard and Edgers’ method for estimating this long-term settlement as well as the effect of additional surcharge due to afteruse development. Based on the regression of these data, compression indices \( C_{ae} \) and \( C_{ae} \) at different stages of the settlement in the modified method have been calibrated and validated.

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1. Introduction

Landfill is one of the major methods in disposing of municipal solid waste (MSW) in Hong Kong. Lots of environmental drawbacks including smell and loss of valuable land are remained irresolvable. Thus, the public had expressed strong objection on further expansion of the current landfill sites. On the other hand, there are now 13 closed landfill sites (total area of about 300 ha) in Hong Kong (Fig. 1), and a restoration program has been launched since 1999 to transform the closed landfill sites back into green zones for the use of future generations. Improper planning and development on these former landfill sites may result in landslides or unacceptable settlement, releasing the toxic gases and leachate.

In Hong Kong, the Environmental Protection Department (EPD) monitors the ground settlement, leachate and landfill gas emission once a landfill site is closed and this period lasting for 20–30 years is called “aftercare” period. 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 MSW results in the differential settlement, excessive loading or massive building structures can be avoided at this stage. 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 discusses the long-term settlement at Ngau Chi Wan (NCW) and Jordan Valley (JV) landfill sites and the settlement survey data will be analyzed to calibrate and validate the compression indices \( C_{ae} \) and \( C_{ae} \) for various stages in the theoretical models. The purpose of such calibration and validation is to provide empirical data for prediction of settlements of MSW in Hong Kong for future similar afteruse development.

Out of the 13 closed landfill sites, the Architectural Services Department (ArchSD) was responsible for the restoration of NCW and JV landfills to recreational areas which have been opened to the public in the mid-2010. 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 ha, consisting of two separate disposal areas that have been doped to form a series of platforms. The site has now been developed into an archery field, children’s playground, and lawn and basketball courts. Fig. 2 shows the aerial view of NCW landfill after the restoration.
Landfilling operation at JV 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 ha and has now been restored to a model car racing circuit with single storey audience seat, toilets, a greenhouse and an education centre. Fig. 3 shows the aerial view of JV landfill after the restoration.

Continuous ground settlement monitoring was carried out by the Civil Engineering Office (CEO), EPD and the contractors of the afteruse development of NCW and JV landfills. NCW and JV recreation projects were completed, and both facilities have been opened to the public since 2010. A year after the opening of the parks, ground and building settlements are still being monitored though the rates of settlement have been diminished. Settlement versus time graphs were plotted for both NCW and JV sites to investigate the trend of settlement, with a view to calibrate and validate the methods of prediction of landfill settlement for future afteruse development of closed landfill sites.

Fig. 1. Closed landfill sites in Hong Kong (EPD, 1997). 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; TKO/I/II/III: Tseung Kwan O Stage I/II/III.

Fig. 2. Aerial view of NCW landfill.

Fig. 3. Aerial view of JV landfill.

2. Waste settlement

Settlement is a major geotechnical aspect of the restoration and development of closed landfill sites. MSW settlement will cause problems for afteruse development, such as severe distortion and damage to buildings, sagging of surface channels or ground, resulting in water ponding, reversed flow of underground drain, cracking of surface paving and surface channels causing infiltration of water into MSW, and rupture of utility lines/underground drains (Yim, 1989). MSW settlement is both irregular and excessive. The maximum settlement depends mainly on the thickness of MSW. While the total settlement can be relatively easier to be handled, differential settlement is, however, another major concern, as it will induce building or hard pavement distortion or cracks leading to unserviceability. It is therefore important to have a proper estimate of the total and differential settlements of MSW for development in landfill sites.

2.1. Mechanism of waste settlement

The mechanism of MSW settlement is complex, and the settlement can be attributed mainly to short-term deformation followed by long-term biodegradation of MSW. Typical settlement curve for MSW is shown in Fig. 4 (modified from Grisolia and Napoleoni (1995) and Liu et al. (2006)). Settlement is classified into five stages as follows:

1. Stage I (initial): the instant mechanical compression induced by compression of highly deformable waste components;
2. Stage II (primary): the mechanical settlement due to continuous slippage or reorientation of waste;
3. Stage III (secondary): the mechanical deformation due to the creep of waste and the initial decomposition of organic material;
4. Stage IV (decomposition): the decomposition of organic material; and
5. Stage V (residual): the residual deformation of mechanical settlement and organic decomposition.

Stages I and II settlement will be completed in around 1 to 3 months after closure of the refuse filling operation, and hence is not a main concern in afteruse development. Stages III to V settlement involves mechanical compression of waste and its time-dependent biodegradation, and is a major concern for the rehabilitation of the landfill sites. Among these stages, Stage IV shows a considerable amount of settlement, as the organic material is converted into liquid and gaseous forms during the biodegradation of waste. The curve for each stage tends to be linear with logarithm of time.

Fig. 4. General settlement curve of MSW with time (modified from Grisolia and Napoleoni (1995) and Liu et al. (2006)).
Table 1
Summary of settlement behaviour of landfill (Sarsby, 2000).

<table>
<thead>
<tr>
<th>Source</th>
<th>Waste type</th>
<th>Settlement of depth of MSW (%)</th>
<th>Time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edgers and Noble (1992)</td>
<td>Municipal solid</td>
<td>25–50</td>
<td>20 years</td>
</tr>
<tr>
<td>Edil et al. (1990)</td>
<td>Municipal solid</td>
<td>5–30</td>
<td>Most occurs in 2 years</td>
</tr>
<tr>
<td>Francis (1993)</td>
<td>Household refuse</td>
<td>Up to 20</td>
<td>65% occurs in 3 years, most occurs in 15 years</td>
</tr>
<tr>
<td>Hutzler (1981)</td>
<td>Household</td>
<td>Overall 15–20</td>
<td>Around 20 years</td>
</tr>
<tr>
<td>Jessberger (1994)</td>
<td>Mixed landfill</td>
<td>About 20</td>
<td>15–20 years</td>
</tr>
<tr>
<td>Noble et al. (1988)</td>
<td>Household</td>
<td>20</td>
<td>20 years</td>
</tr>
<tr>
<td>Sarsby (1987)</td>
<td>Household and commercial</td>
<td>6–9</td>
<td>5 years</td>
</tr>
</tbody>
</table>

Table 1 summarizes the literature on the total settlement of landfill, and the general consensus is that the majority of the settlement will mostly have been completed in around 20 years, though there will be some residual settlement which will occur for a longer period of time. According to Park and Park (2009), the estimated long-term settlement in 50 years is about 30% of the depth of MSW.

2.2. Settlement estimation (literature review)

Numerous settlement estimation methods (e.g. Gibson and Lo, 1961; Sowers, 1973; Edil et al., 1990; Ling et al., 1998) were developed. Soil mechanics models have usually been adopted to predict the settlements in landfill subjected to the waste mass and the applied loading, although Dunn (1995) and Bowders et al. (2000) stated that such soil mechanics models should be supplemented with empirical equations, and that even with such supplement, prediction only gives an estimate and such models should be treated carefully and conservatively.

2.2.1. Sowers’ method

Sowers (1973) separated the settlement into primary settlement (ΔH_p) and secondary settlement (ΔH_s) stages (Fig. 5), and used a regression approach to estimate the appropriate coefficient:

ΔH = ΔH_p + ΔH_s = H_c[e log10(P_0 + ΔP)/P_0 + H_t1 C_e log10(t_{n+1}/t_{11})] (1)

where H is the initial thickness of waste; ΔH is the settlement; t_{11} is the starting time for secondary settlement; H_t1 is the thickness of waste at the beginning of the long-term settlement (i.e. thickness at t_{11}); ΔP is the change in applied pressure; C_e = C_c/(1 + ε_o), in which ε_o is the void ratio, C_c is the compression index; C_a is the long-term compression index; P_0 is the initial overburden pressure; t_{n+1} is the time of interest.

Sowers’ model (Eq. (1)) is one of the most widely used approaches for settlement prediction for landfill because of its simplicity and familiarity. However, the major drawback of the method is that it does not allow for the long-term settlement to be converging as described by Grisolia and Napoleoni (1995) and Park and Park (2009) in Fig. 4. Sharma and De (2007), using Sowers’ model, summarized the values of C_e and C_a from various literatures (Table 2) for settlement estimation.

Table 2
Values of C_e and C_a in Sowers’ model (Sharma and De, 2007).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Primary C_e</th>
<th>Secondary C_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sowers (1973) [for ε_o = 3]</td>
<td>0.1–0.41</td>
<td>0.02–0.07</td>
</tr>
<tr>
<td>Zoino (1974)</td>
<td>0.15–0.33</td>
<td>0.013–0.03</td>
</tr>
<tr>
<td>Converse Davis Dixon Associates (1975)</td>
<td>0.25–0.3</td>
<td>0.07</td>
</tr>
<tr>
<td>Rao et al. (1977)</td>
<td>0.16–0.235</td>
<td>0.012–0.046</td>
</tr>
<tr>
<td>Landva et al. (1984)</td>
<td>0.2–0.5</td>
<td>0.0005–0.029</td>
</tr>
<tr>
<td>Wall and Zeiss (1995)</td>
<td>0.21–0.25</td>
<td>0.03–0.056</td>
</tr>
<tr>
<td>Gabr and Valero (1995)</td>
<td>0.2–0.23</td>
<td>0.015–0.023</td>
</tr>
</tbody>
</table>

2.2.2. Bjarnard and Edgers’ method

Sowers’ model, however, only includes a single value of C_e, which is assumed to be constant throughout various stages of settlement, and hence has not taken into account of different mechanisms of landfill settlement in different stages. Oweis and Khera (1998) summarized the values of C_e for different types of waste published in the literature, and found that the values of C_e, indeed, vary with the age of the waste. Bjarnard and Edgers (1990) modified Sowers’ model to take into account of different mechanisms of settlement at different stages. Their method is an improvement over Sowers’ model, as it includes different C_e values for different stages of settlement. Fig. 6 shows the typical settlement curve in Bjarnard and Edger’s model, and their equation is written as follows:

ΔH = C_s log10(P_0 + ΔP)/P_0 + H_t1 C_a(1) log10(t_{n+1}/t_{11}) + H_t2 C_a(2) log10(t_{n+1}/t_{12}) (2)

![Fig. 5. Typical settlement curve in Sowers’ model.](image)

![Fig. 6. Bjarnard and Edgers’ model.](image)
where \( H(t_2) \) is the thickness of waste at the beginning of the decomposition settlement (i.e., thickness at \( t_2 \)), \( C_\alpha \) is the compression ratio, \( C_\alpha(1) \) is the Stage III compression index, \( C_\alpha(2) \) is the Stage IV compression index, and \( t_2 \) is the starting time for long-term settlement.

The drawback of Bjarnard and Edgers’ method is that it requires the calibration of a number of parameters \((C_\alpha(1), C_\alpha(2), t_1, t_2)\) in order to predict the total settlement. Again, it does not allow for the long-term settlement to be converging as described by Grisolia and Napolioli (1995) and Park and Park (2009) in Fig. 4.

2.2.3. Modified Bjarnard and Edgers’ method

It is noted from Grisolia and Napolioli (1995) and Park and Park (2009) that the settlement will become less and less in the long-term, i.e. converging residual settlement. This paper therefore suggests modifying the Bjarnard and Edgers’ method for estimating this long-term settlement as follows:

\[
\Delta H = H(t_2) C_\alpha(1) \log_{10} \frac{P_0 + \Delta P}{P_0} + H(t_1) C_\alpha(1) \log_{10} \frac{t_2}{t_1} + H(t_2) C_\alpha(2) \log_{10} \frac{t_3}{t_2} + H(t_3) C_\alpha(3) \log_{10} \frac{t(n+1)}{t(n)}
\]

(3)

where \( H(t_2) \) is the thickness of waste at the beginning of the residual settlement, \( C_\alpha(3) \) is the Stage V compression index, and \( t_3 \) is the starting time for residual settlement.

The settlement curve resembles those from Grisolia and Napolioli (1995) and Liu et al. (2006) (Fig. 7). The regression method will be used to find out the compression index \( C_\alpha \).

2.2.4. Suggested formula for estimating settlement of afteruse development

In a typical afteruse development, additional loading to MSW will be imposed, and hence additional settlement will be induced. Application of external loads (such as constructing building, backfill soil, etc.) on landfill site will induce additional ground settlement which will occur within a few months to one or two years as observed in the NCW and JV sites. This phenomenon is illustrated by settlement curve in Fig. 8.

Sharma and De (2007) studied the settlement under external loads, such as final cover systems or construction of structures. The study concluded that the intensity of external loads is much smaller than that due to deadweight of MSW in landfill. Most structures during the afteruse development are constructed long after a landfill has been closed. Therefore, most deadweight settlement has been completed by the time when externally applied load is introduced. Since the amount of deadweight settlement during this period is very small, Sharma and De (2007) did not consider that it is necessary to combine the calculation for deadweight and externally applied loads, and the following equation was suggested:

\[
\Delta H_{EL} = H(t_2) C_\alpha(EL) \log_{10} \frac{t_2}{t_1}
\]

(4)

where \( \Delta H_{EL} \) is the settlement at time \( t_2 \) after external load application, \( t_1 \) is the time for short-term settlement, \( t_2 \) is the time of interest since the external load application, \( H(t_2) \) is the thickness of refuse fill at time \( t_1 \), and \( C_\alpha(EL) \) is the coefficient of long-term compression due to external loads.

However, one of the drawbacks for the above equation is that the intensity of external load which causes additional settlement has not been taken into account. In both NCW and JV sites, noticeable increase in ground settlement after the commencement of construction was observed in addition to the continuous decomposition/residual settlement. As the intensity of external loads for both projects was in the range of 10–20% of the total weight of waste, such intensity cannot be neglected; thus, Sharma and De’s suggestion in the above equation is not appropriate in determining the additional settlement right after construction in both sites. On the other hand, Eq. (5) suggested by Sowers’ model for short-term settlement has considered the change in applied pressure throughout the whole waste depth, and is more suitable for determining the additional settlement due to externally applied load for both NCW and JV projects:

\[
\Delta H_p = H(t_2) C_\alpha(EL) \log_{10} \frac{P_0 + \Delta P}{P_0}
\]

(5)

In practice, the most useful information in the design of the afteruse development of a landfill is the expected total settlement of the site after the commencement of development. In the determination of this expected settlement, this paper therefore suggests the following formula:

\[
\Delta H = H(t_2) C_\alpha(EL) \log_{10} \frac{P_0 + \Delta P}{P_0} + H(t_3) C_\alpha(3) \log_{10} \frac{t(n+1)}{t(n)}
\]

(6)

where \( t(n) \) is the time at the commencement of development.

The first term at the right side of equal sign represents the additional settlement due to externally applied load (e.g., final cover systems or construction of structures or fills of the afteruse development), and the second term stands for the long-term settlement after the commencement of the afteruse development.

3. Settlement to date of NCW and JV projects

In the 1970s, CEO had installed a number of settlement markers on site to monitor the settlement of MSW in all the 13 landfill sites during and after the cessation of landflling operation. Yim (1989) summarized the monitoring data obtained for NCW site
from 1978 to 1985, which serve as invaluable data for the Stages II and III settlement. In 1999, EPD launched the initial restoration program on these sites in order to prepare them for the afteruse development. The program included installing 32 and 9 settlement markers on NCW and JV sites respectively, which have then been monitored annually. During the construction works of the afteruse development, ArchSD also installed additional settlement markers on buildings and platforms, which have been monitored monthly. Continuous monitoring was carried out by the afteruse contractors during the maintenance period. After that, a land surveyor was employed to carry out quarterly the ground settlement monitoring. Up till now, ground and building settlements are still being observed; but the rates of settlement have been diminished. Table 3 shows the updated settlements.

Simultaneously, EPD still carried out surveying to its settlement markers annually to monitor the settlement of the closed landfill sites. Settlement data from EPD markers have therefore been available since 1999; thus these data were useful to illustrate the overall trend of the ground settlement. The overall trend of ground settlement for NCW and JV landfills was plotted in Figs. 9–11 using the data obtained from CEO and EPD. For NCW site (Fig. 9), the data representing settlements between 1976 and 1985 were obtained from CEO and that between 2000 and 2012 were obtained from EPD. Fig. 10 shows the snapshot from 2000 to 2012. For JV site (Fig. 11), the settlement data were obtained from EPD. On the other hand, settlement data recorded during construction are useful in determining the compression index (C_{ce}) due to the external load.

It must be acknowledged that the settlements records obtained from CEO and EPD are important and necessary in establishing the parameters C_{a(2)} and C_{a(3)} for settlement prediction. The records obtained during the construction of the afteruse development are only snapshots of the whole history of settlement and not adequate for prediction of future settlement.

4. Settlement after construction of afteruse development

4.1. Primary and secondary settlements (Stages II and III)

Yim (1989) summarized the monitoring data (Table 4) obtained from NCW landfill by CEO from 1978 to 1985, which serve as the data for Stages II and III settlement. The stage compression indexes (creep rates) were calculated due solely to the deadweight of the refuse and no surcharge effect has been considered. The average compression index (creep rate) was found to be C_{a(1)} = 0.055.

4.2. Decomposition and residual settlements (Stages IV and V)

The monitoring results obtained from MSW at NCW landfill since 1999 provide data for Stages IV and V settlement calculation. All such data on the settlement curve are plotted in Fig. 12.

In the typical settlement curve (Fig. 7), the rate of settlement will continue with C_{a(2)} and C_{a(3)} after the secondary settlement against logarithm of time. It is difficult to find an accurate new C_{a(3)} for “afteruse” based on the data obtained from afteruse construction as the period is too short. Instead, C_{a(3)} can be obtained from the data obtained from the aftercare period, i.e. before the construction of the afteruse development, which is much longer provided that the afteruse development commenced long enough after the closure of the landfill operation, e.g. over 20 years. Settlement data obtained from 1998 to 2011 for both NCW and JV sites are therefore plotted against the logarithm of time in Figs. 12 and 13 respectively. Based on the settlement analysis, C_{a} at different stages can be calculated by the following equation using regression method:

$$C_a = \frac{\Delta H}{H \log_{10}(t_{n+1}/t_1)} \quad (7)$$

4.3. Average compression indexes obtained from the projects

Review of the settlement data for the two projects was carried out. As only those data from 1978 to 1985 and from 1999 to 2010 are available, snapshots on the settlement of these periods are then investigated in detail. The compression indexes for Stages III, IV and V are therefore found by the best-fit regression approach as follows:

\[ C_{a(1)} = \text{compression index during Stage III settlement} = 0.0438–0.0714 \text{ (from 1978 to 1985 in Table 4)} \]
\[ C_{a(2)} = \text{compression index during Stage IV settlement} = 0.045–0.07 \text{ (from 2000 to 2005 in Figs. 12 and 13)} \]
\[ C_{a(3)} = \text{compression index during Stage V settlement} = 0.022–0.035 \text{ (from 2006–2008 in Figs. 12 and 13)} \]

### Table 3

Settlement record in NCW and JV sites at different stages.

<table>
<thead>
<tr>
<th>Site</th>
<th>Stage</th>
<th>Period</th>
<th>Maximum settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCW (site closed since 1977)</td>
<td>After closure</td>
<td>1978–1985 (7 years)</td>
<td>4400</td>
</tr>
<tr>
<td></td>
<td>Before aftercare</td>
<td>1985–1999 (14 years)</td>
<td>No record</td>
</tr>
<tr>
<td></td>
<td>Aftercare</td>
<td>1999–2008 (9 years)</td>
<td>396</td>
</tr>
<tr>
<td></td>
<td>Construction of afteruse development</td>
<td>2008–2010 (2 years)</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>Defect liability period (DLP)</td>
<td>2010–2011 (1 year)</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>After DLP</td>
<td>2011–2012 (1 year)</td>
<td>41</td>
</tr>
<tr>
<td>JV (site closed since 1990)</td>
<td>After closure</td>
<td>1990–1998 (8 years)</td>
<td>No record</td>
</tr>
<tr>
<td></td>
<td>Aftercare</td>
<td>1998–2008 (10 years)</td>
<td>833</td>
</tr>
<tr>
<td></td>
<td>Construction of afteruse development</td>
<td>2008–2010 (2 years)</td>
<td>274</td>
</tr>
<tr>
<td></td>
<td>DLP</td>
<td>2010–2011 (1 year)</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>After DLP</td>
<td>2011–2012 (1 year)</td>
<td>56</td>
</tr>
</tbody>
</table>

### Table 4


<table>
<thead>
<tr>
<th>Monitoring station</th>
<th>Fill thickness (m)</th>
<th>Period (year)</th>
<th>(\Delta H/H) (%)</th>
<th>Stage III compression index C_{a(1)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>B3</td>
<td>30</td>
<td>7.8</td>
<td>12.06</td>
<td>0.0714</td>
</tr>
<tr>
<td>B4A</td>
<td>34</td>
<td>7.3</td>
<td>7.31</td>
<td>0.0515</td>
</tr>
<tr>
<td>B5</td>
<td>25</td>
<td>4.7</td>
<td>9.71</td>
<td>0.0491</td>
</tr>
<tr>
<td>B7</td>
<td>41</td>
<td>7.3</td>
<td>7.10</td>
<td>0.0438</td>
</tr>
<tr>
<td>B9</td>
<td>41</td>
<td>7.3</td>
<td>10.72</td>
<td>0.0580</td>
</tr>
</tbody>
</table>
5. Additional settlement after construction of afteruse development

5.1. Unit weight of MSW and additional surcharge

In order to estimate the additional settlement due to externally applied loads as Eq. (6), the density of MSW has to be determined. Yim (1989), by counting the weight of MSW dumped into NCW site, estimated the density of refuse to be in the range of 9.5 kN/m$^3$ to 11.9 kN/m$^3$ (Table 5). Over years after site closed, the density is anticipated to be increased due to self-compaction. Therefore, an average density will be used in calculating the additional settlement. The externally applied load on top of the refuse for both NCW and JV landfills was at a maximum of 43 kPa (2 m thick of soil plus 5 kPa for imposed load).

5.2. Validation of $C_{ce}$

From Eq. (6), compression index ($C_{ce}$) is an unknown factor. To determine $C_{ce}$, MSW was divided into layers at 1 m interval and additional stress at each layer ($\Delta P$) was calculated based on the method of Lambe and Whitman (1979). Ground settlement data recorded during the construction period were also used. For JV and NCW sites, the site formation works commenced in early 2008 and 2009 respectively, and the ground settlement monitoring stations were installed at the time of project commencement. The ground settlement data during construction period from 2008 to 2012 for JV site are plotted in Fig. 14.

The settlement after construction consists of two parts, i.e. long-term settlement due to decomposition of MSW and the additional settlement due to externally applied loads. This phenomenon
can be illustrated by the ground settlement data of ASM06 (Fig. 14) in JV landfill. The ground settled sharply for 150 mm from October 2008 to January 2009, and after that the rate of settlement gradually slowed down after April 2009. The settlement due to additional surcharge may occur longer than the construction period, i.e. it may occur immediately and thereafter (creep effect).

By knowing the depth of MSW, density of waste, additional surcharge and $C_{ce}$, $C_{ce}$ for individual ground settlement point can be back calculated. Table 6 shows the results of $C_{ce}$ calculated from all the representative ground settlement data of both projects and their average values, i.e. average $C_{ce} = 0.0463$ and 0.0563.

Individual values of compression index ($C_{ce}$) of the monitoring stations due to externally applied loads were found within

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Unit weights of MSW (Yim, 1989).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill site</td>
<td>Period</td>
</tr>
<tr>
<td>NCW(west valley)</td>
<td>26/1/1976–10/12/1977</td>
</tr>
</tbody>
</table>
Fig. 13. $\Delta H/H$ vs. log time for JV landfill (EPD markers) from 1998 to 2012.

Fig. 14. Ground settlement in JV landfill during construction period (ASM06).

Table 6
Range of compression index $C_{ce}$ due to externally applied loads.

<table>
<thead>
<tr>
<th>Site</th>
<th>Station</th>
<th>$\Delta H_p$ (2008–2012) using $C_u$ of past history</th>
<th>Present settlement (during construction) (mm)</th>
<th>Immediate settlement (m)</th>
<th>$C_{ce}$</th>
<th>Avg. $C_{ce}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCW ($C_{ce(3)} = 0.035$)</td>
<td>ASM01</td>
<td>0.033</td>
<td>0.226</td>
<td>0.193</td>
<td>0.041</td>
<td>0.046</td>
</tr>
<tr>
<td></td>
<td>ASM02</td>
<td>0.033</td>
<td>0.269</td>
<td>0.236</td>
<td>0.057</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASM03</td>
<td>0.028</td>
<td>0.260</td>
<td>0.232</td>
<td>0.052</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASM04</td>
<td>0.028</td>
<td>0.191</td>
<td>0.164</td>
<td>0.044</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASM05</td>
<td>0.024</td>
<td>0.187</td>
<td>0.163</td>
<td>0.038</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASM06</td>
<td>0.021</td>
<td>0.215</td>
<td>0.194</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASM07</td>
<td>0.037</td>
<td>0.197</td>
<td>0.161</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td>JV ($C_{ce(3)} = 0.022$)</td>
<td>ASM04</td>
<td>0.072</td>
<td>0.224</td>
<td>0.152</td>
<td>0.065</td>
<td>0.056</td>
</tr>
<tr>
<td></td>
<td>ASM06</td>
<td>0.096</td>
<td>0.457</td>
<td>0.361</td>
<td>0.092</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASM08</td>
<td>0.144</td>
<td>0.348</td>
<td>0.204</td>
<td>0.041</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASM13</td>
<td>0.072</td>
<td>0.155</td>
<td>0.083</td>
<td>0.027</td>
<td></td>
</tr>
</tbody>
</table>
the range of 0.027–0.092, which were several times smaller than the values suggested by Sowers (1973) and those suggested in the literature (Table 2). One of the possible reasons is that Sowers’ figure occurs at initial and primary stages (Stages I and II) when the void ratio is high. In the present cases in the residual stage (Stage V), there has been a substantial decrease in void ratio in MSW throughout the mechanical compression and biological decomposition process throughout the years resulting in a smaller compression index.

6. Conclusions

Accurately predicting long-term settlement of landfills is a challenge because of the heterogeneous characteristics of MSW and lack of long-term settlement records on landfill sites in Hong Kong. By reviewing the settlement monitoring data at NCW and JV landfills over a 30-year period, it is possible to develop a settlement model for MSW in Hong Kong that has allowed estimation of future settlement; Eq. (6) can be used for such purpose. Regression approach is a good approximation and should be used to obtain the relevant compression indexes based on previous aftercare settlement data. From the settlement data obtained from the project sites discussed, the compression indexes \( C_{0(3)} \) for Stage V settlement can be taken as ranging from 0.02 to 0.04 for estimating the long-term settlement. The compression index \( C_{ce} \) due to externally applied load of the afterlife development is about 0.04–0.06.

However, if the afterlife development starts too soon after the closure of the landfill, e.g. earlier than 15 years, there is still some active decomposition (Stage IV) in progress and the settlement will be high. In such case, both Stage IV settlement with compression indexes \( C_{0(2)} = 0.045–0.07 \) and Stage V settlement should be considered.

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Wong CT. is a Chief Structural Engineer of the Architectural Services Department (ArchSD). He graduated from the Hong Kong Polytechnic in 1976. Since then, he undertook civil and structural engineering training in Palmer and Turner and became a Chartered Engineer in 1980. Wong joined the Government in 1981 working in ArchSD responsible for the design and construction of various types of building structures. Wong has completed many school buildings, markets, parks, offices, indoor game halls, swimming pool complexes and sport grounds. He was in charge of the two afteruse development of the landfill projects at Ngau Chi Wan and Jordan Valley in Hong Kong. His main interests are foundations, structural steel and use of different construction materials.