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Quantifying the long-term settlement of municipal solid wastes in landfills based on global navigation satellite system

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ABSTRACT

The settlement of municipal solid wastes (MSWs) is one of the important components in the design, construction, operation and management of landfills. The secondary settlement induced by mechanical creep and biodegradation is the most significant settlement in the total settlement of MSWs. This paper presents the installation and data collection of geodetic monitoring networks based on the global navigation satellite system (GNSS). The settlement of three landfill cells with different ages was monitored for 2 years. The ages of MSWs in those monitored cells at the first year of monitoring were 7, 8 and 14 years and those at the second year were 8, 9 and 15 years. The settlement rates for landfill cells of the age of 7, 8, 14 and 8, 9, 15 years are 0.53, 0.35, 0.06 mm/day and 0.46, 0.36, 0.05 mm/day, respectively. The comparison between the primary and secondary compression ratios of MSWs from field monitoring and bioreactor experiments indicates that the results from bioreactor experiments may not be suitable for direct use in the prediction of the settlement of MSWs.

Keywords: global navigation satellite system, geodetic monitoring network, municipal solid waste, landfill

1 INTRODUCTION

Landfilling has been an economically affordable and environmentally acceptable method for disposal of municipal solid wastes (MSWs) in both developing and developed countries (Xie et al., 2022, 2023a). The amount of MSWs disposed in landfills accounts for over 50% (Chen et al., 2021), 53% (Mukherjee et al., 2020) and 37% (Pickin et al., 2020) of total waste production in China, USA and Australia, respectively. The settlement of MSWs has been one of the most important factors in the design and management of landfills. The typical settlement of landfilled MSWs ranges from 15% to 50% of the initial thickness of the waste cell, depending on the geotechnical properties of MSWs, operation methods of landfills and local climates (Xie et al., 2018).

The settlement of MSWs results from the rearrangement of MSWs particles due to physical and mechanical processes, chemical reactions, breakdown of MSWs particles by mechanical compression and decomposition, biodegradation of MSWs and mechanical creep (Gao and Kavazanjian, 2022, Xie et al., 2023b). Depending on the mechanisms, the settlement of MSWs can therefore be categorized as immediate, primary, secondary and residual settlement (Fei and Zekkos, 2013). The immediate settlement results from the direct response of MSWs due to stress increment. The primary compression (or initial creep) of MSWs results from the deformation, movement and rearrangement of particles due to stress increment and mechanical creep. Due to the high porosity and hydraulic conductivity of MSWs, the majority of primary compression can be completed in few months in landfills but few days or weeks in laboratory scale bioreactors (Xie et al., 2023a). The secondary settlement included the mechanical creep and biocompression and is the most significant component of the total settlement. The residual compression of MSWs results from the creep of MSWs and is a function of vertical stress and time. The primary, secondary and residual compression ratio is generally used to describe the secondary settlement of MSWs (Fei and Zekkos, 2018, Xie, 2022, Xie et al., 2023a), as expressed in Eq. (1). To improve the design, construction, operation and management of landfills, it is important to collect reliable and accurate information about the settlement of MSWs.

$$C_{\alpha i} = \frac{\Delta \varepsilon_i}{\Delta \log\left(\frac{t}{t_i}\right)} \quad (1)$$

where ε_i = the vertical strain occurred in the primary, secondary and residual compression,
$C_{\alpha i}$ = the primary, secondary and residual compression ratio,
t_i = the time of the start of the primary, secondary and residual compression.

Common methods to monitor the long-term settlement of MSWs in landfills are the settlement plate (e.g., Bareither et al., 2012, Simões and Catapreta, 2013) and electronic total stations (e.g., Peng et al., 2016). The major drawbacks of those methods are related to the expensive labour costs (particularly in terms of large and complex areas) and risks to personnels when working in the dangerous areas (Filkin et al., 2022). The settlement needs to be regularly collected by personnels to obtain continuous settlement profile of landfill cells. The application of geodetic monitoring network based on the global navigation satellite system (GNSS) means those issues can be partially resolved. The settlement of the monitoring points can be automatically recorded with time and stored. The settlement data can be collected at lower frequencies.

This paper presents the installation of the geodetic monitoring network based on the global navigation satellite system (GNSS) to obtain the settlement of MSWs in the Mugga Lane Landfill, Australian Capital Territory (ACT), Australia. The settlement of MSWs in three cells with different ages was monitored for the period of 2 years. The obtained settlement data was used to build the settlement profile of MSWs with time.

2 METHODOLOGY

2.1 Mugga Lane Landfill

The Mugga Lane Landfill is located near the northeast corner of Mugga Lane, Long Gully Road, Symonston, Australian Capital Territory (ACT), Australia. It is the only landfill site in the ACT area. The landfill covers an area of 123 ha. The Mugga Lane Landfill receives 850,000 m^3 (171,000) tons of fresh MSWs annually. The composition of fresh MSWs disposed in 2009, 2017 and 2019 in the landfill site has been reported by Quinn (2010), Cumming (2017) and Xie et al. (2022), as summarized in ***Table 1***. The percentage of each component of fresh MSWs is relatively stable during 2009 and 2019, except the soil and textile content. The settlement caused by those materials is much less significant compared to other biodegradable or highly compressible components such as food and plastic). The percentage of organic (biodegradable) contents during 2009 and 2019 is stable, ranging from 43.0% to 48.4%. Therefore, it is assumed that the landfill cells with different ages (ML1, ML2 and ML3) can be regarded as the same landfill cell with different ages.

The composition of fresh MSWs disposed in the Mugga Lane Landfill is different from the high food content MSWs and low food content MSWs (LF-MSWs). The proportion of biodegradable contents such as food and paper is lower than the typical LF-MSWs, and the percentage of non-biodegradable contents (over 50%) is much higher than other MSWs (Chen et al., 2018, Xie and Xue, 2023). The high soil content results from the application of daily intermediate soil cover. After completion of waste disposal, one layer of intermediate soil (typically 0.25 m) was placed above the fresh MSWs. Although the soil was usually removed on the second day, significant number of particles could be left in the MSWs body due to high void ratio of fresh MSWs.

Table 1. *Composition of MSWs in Mugga Lane Landfill in 2009, 2017 and 2019*

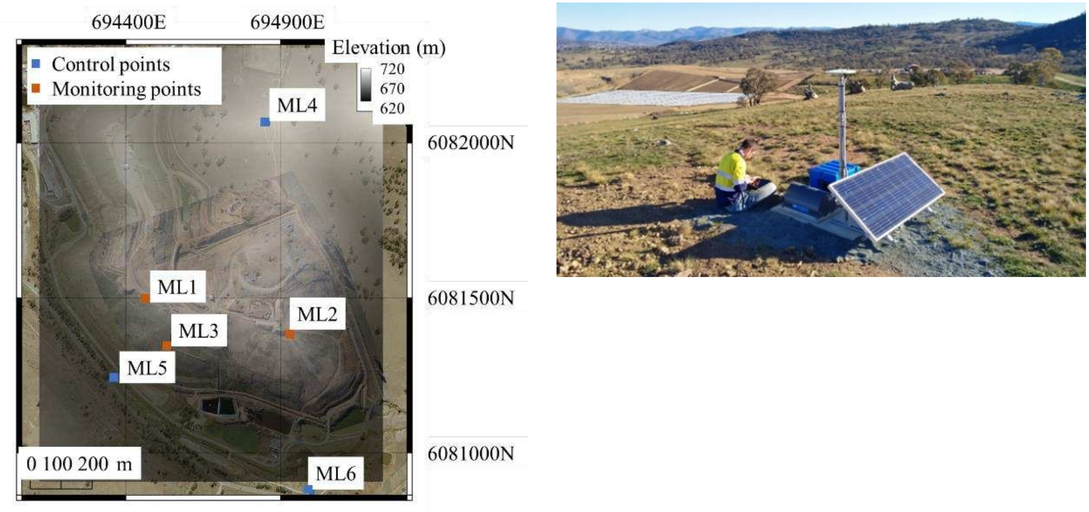
Constitution	Year		
	2019	2015	2009
Soil	32.9%	31.3%	16.6%
Paper and cardboard	19.3%	18.0%	15.3%
Food	16.2%	13.3%	19.8%
Vegetation	1.4%	3.1%	8.3%
Sludge	0.0%	1.6%	0.0%
Wood and wood products	8.1%	8.6%	5.0%

Textiles	3.7%	2.6%	12.5%
Glass	2.2%	2.9%	3.6%
Plastics	11.0%	10.3%	14.0%
Metal	0.4%	1.4%	2.8%
Construction waste	4.7%	6.8%	2.0%

2.2 Installation of monitoring system

The settlement of MSWs in three different landfill cells with different MSWs ages (7, 8 and 14 years) was measured. To determine the settlement of those cells, the geodetic monitoring networks were installed at six different locations at the Mugga Lane Landfill in August 2020. The six monitoring networks included three monitoring points (ML1, ML2, ML3) and another three reference points (ML4, ML5, ML6), as shown in ***Figure 1*** (a).

The ages of MSWs at ML1, ML2, ML3 were 8, 7 and 14 years at installation. After one year of the monitoring, the ages of MSWs at ML1, ML2, ML3 became 9, 8 and 15 years. The ML3 was installed near the middle of the slope in the 14-year-old cell. The typical settlement of MSWs in the middle of the slope varied from 30% to 70% of the total settlement (Jones and Dixon, 2005). Therefore, the actual settlement from the top of the cell was assumed to be twice as that measured from ML3. The ML4 and ML5 were installed within the landfill but outside any previously closed cells. The ML6 was installed outside of the landfill for reference. At each monitoring location, a 1 m × 1 m × 0.1 m concrete slab was installed with a GNSS antenna and antenna pole, a GNSS receiver and a solar panel (***Figure 1*** (b)). Therefore, no additional powder supply or frequent data collection was required. The settlement at the monitoring points was recorded automatically on daily basis.



(a) Location of the global navigation satellite system

(b) Setup of the global navigation satellite system

Figure 1. *Setup and installation of the geodetic monitoring network at the Mugga Lane Landfill (modified from Xie et al. (2023b))*

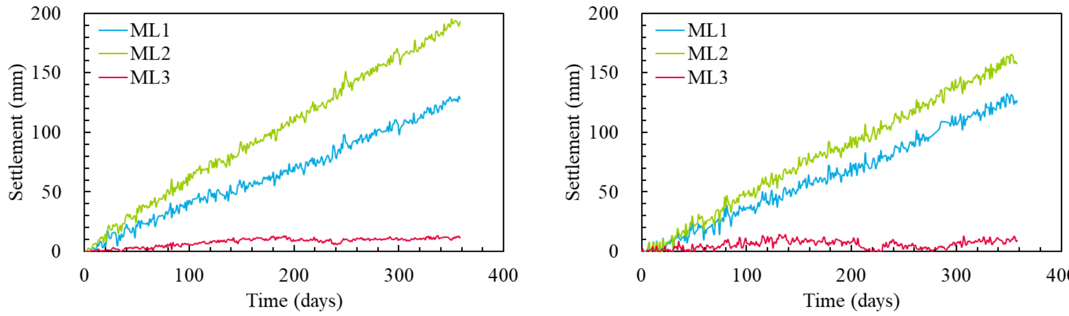
2.3 Settlement data collection

The processing strategy for the coordinate time series of the GNSS sites can be summarized as the following (Xie et al., 2023b). The GPS-only data sampled at 30 seconds were used to form the daily coordinates. The global positioning system (GPS) data was processed by the Bernese version 5.2 method with a network differential approach Dach et al. (2015). The motion of the Australian plate was subtracted according to the database from ICSM (2021). The coordinates were converted from geocentric to a local topographic coordinate system prior to differencing each daily observation from the first epoch. Therefore, the coordinate time series could express local-only movement in comparison to the first observation.

3 RESULT AND DISCUSSION

3.1 Settlement rate of MSWs

Figure 2 (a, b) presents the settlement of landfill cells with different ages in the first and second year after the installation of the monitoring networks. The settlement of landfill cells in the first year of monitoring is higher than that in the second year of monitoring, indicating the reduction in the settlement rates with time. The relationship between the settlement and time is almost linear. Therefore, the settlement rates of landfill cells can be obtained from the slope of the settlement and time curve. The settlement rates of landfill cells with age of 7, 8, 14 years and 8, 9, 15 years are 0.53, 0.35, 0.06 mm/day and 0.46,0.36, and 0.05 mm/day, respectively, as summarized in ***Table 2***.



(a) Settlement of the landfill cells in the first year of monitoring

(b) Settlement of the landfill cells in the second year of monitoring

Figure 2. *Monitored settlement of the landfill cells*

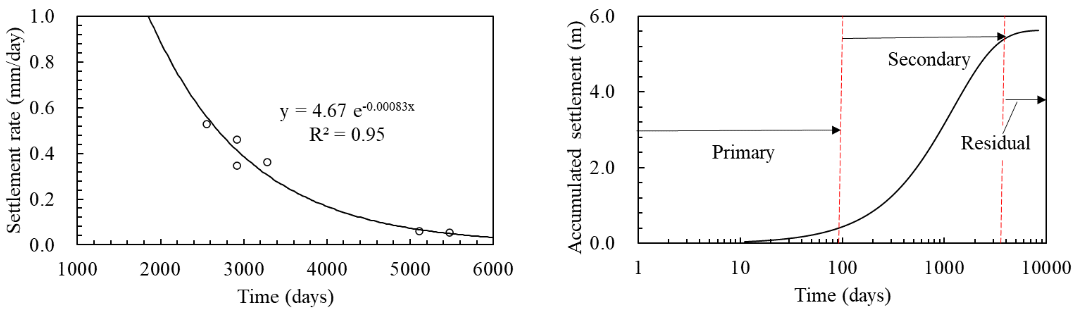
Table 2. *Settlement rates of landfill cells with different ages*

Cell age (years)	Settlement rate (mm/day)
7	0.53
8	0.35
14	0.06
8	0.46
9	0.36
15	0.05

3.2 Accumulated settlement

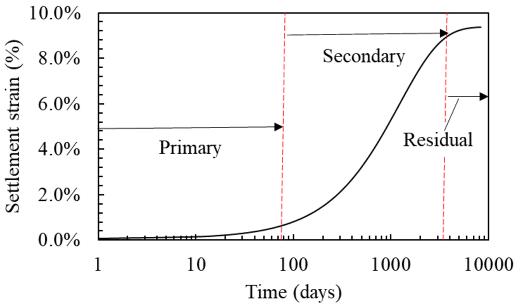
Figure 3 (a) shows the settlement rates and ages of landfill cells based on ***Table 2***. The relationship between the settlement rates and ages of landfill cells can be well described by an exponential curve. As mentioned in 2.1, the composition of MSWs in the three monitored cells does not vary significantly. The settlement monitored in those cells can be regarded as the same landfill cell but with different ages. Therefore, settlement rate with time can be expressed as Eq. (2). The accumulated settlement of MSWs (S_r) in the cell can be obtained by definite integrals of Eq. (2), as presented in ***Figure 3*** (b).

$$S_r = 4.67e^{-0.00083t} \tag{2}$$



(a) Settlement rate of MSWs at different ages

(b) Accumulated settlement of MSWs with time



(c) Accumulated settlement strain of MSWs with time

Figure 3. *Settlment rate and accumulated setltment of MSWs*

3.3 Compression ratios

Considering the total thickness of the cell is around 60 m, the accumulated strain can be plotted in ***Figure 3*** (c). The primary, secondary and residual compression can be determined based on the slope of the curve. The start of primary compression is generally regarded in 1 day as the immediate settlement assumed to be completed within 1 day. The experiments conducted by Zekkos et al. (2017) also indicate that the immediate compression could be completed in few hours after the application of stress. Based on Eq. (1), the primary, secondary and residual compression ratios of MSWs in the landfill cell are 0.0037, 0.0719 and 0.0033.

Figure 4 compares the primary compression ratios of MSWs with different dry unit weights, based on the results from Zekkos et al. (2017), Xu et al. (2020), Portelinha et al. (2020) and Xie et al. (2023a). The compression ratio of MSWs in the landfill cell is higher than that obtained from experimental investigations. The primary compression ratios of MSWs depends on the compositions, moisture contents, dry unit weights and stress levels. Xie et al. (2023a) used the MSWs with same composition as that collected from Mugga Lane Landfill for the bioreactor model tests of 400 mm diameter. Although the dry unit weights of MSWs used in Xie et al. (2023a) are lower than that in-situ, the primary compression ratios of MSWs in those bioreactors are lower than that in the field (Figure 4). This is attributed to the higher stress levels of MSWs in the field. The stronger compaction energy applied in the field results in higher dry unit weights of MSWs, and therefore higher stress induced by the self-weights. Zekkos et al. (2017) also investigated the compression ratios of MSWs with different fine contents, stress levels and degrees of biodegradation. For MSWs with same fine content and degree of biodegradation, the primary compression ratio increases with stress levels. Therefore, the variation between the stress of MSWs in laboratory bioreactors and real landfill should be considered in the prediction of the settlement of MSWs.

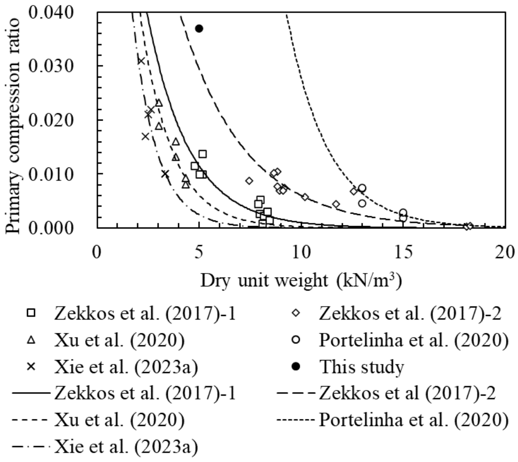


Figure 4 Primary compression ratios of MSWs with different dry unit weights

The secondary compression of MSWs greatly depends on the biodegradation of MSWs. Therefore, the secondary compression ratios are significantly affected by the temperature of MSWs and moisture content, which can be altered by liquid recirculation (Bareither et al., 2012, Portelinha et al., 2020, Xie et al., 2023a). The typical temperature of MSWs in Australian landfills is around 30 ℃, based on the monitoring results from Bouazza et al. (2011). Figure 5 presents the effects of temperature on the secondary compression ratios of MSWs. Depending on the initial dry unit weight and liquid recirculation, the MSWs can be divided into four types: (1) MSWI, MSWs of low dry unit weight (e.g., 3 kN/m^3), with recirculation, (2) MSW II, MSWs of medium dry unit weight (e.g., 5 kN/m^3), with recirculation, (3) MSW III, MSWs with of medium dry unit weight, without recirculation, (4) MSW IV, MSWs with high dry unit weight (e.g., 10 kN/m^3), without recirculation. The secondary compression ratio of this study is similar to that of MSW II. The secondary compression ratio based on field monitoring is higher than expected, which should be similar to that of MSW III. However, the decay rate of MSWs in the field is lower than that in the laboratory or field scale bioreactors due to finer size of MSWs used in the bioreactors (Xie, 2022). This indicates that in addition to the biodegradation, the contribution from other mechanisms such as mechanical creep and rearrangement of particles, can also play an important role in the secondary compression.

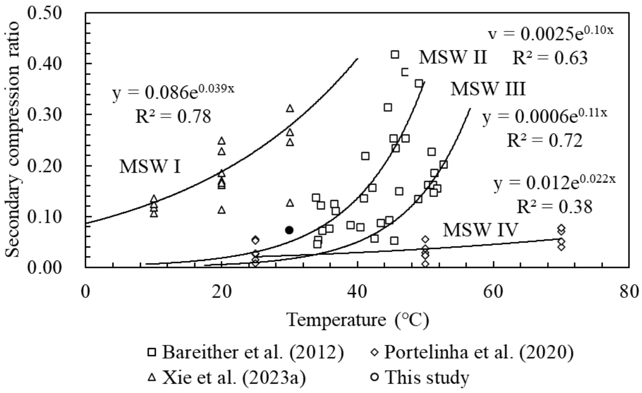


Figure 5 Secondary compression ratios of MSWs under different temperatures

4 CONCLUSIONS

This study presents the installation geodetic monitoring networks based on the global navigation satellite system (GNSS) and settlement data collection in the Mugga Lane Landfill, Australian Capital Territory (ACT), Australia. The settlement rates for landfill cells of the age of 7, 8, 14 and 8, 9, 15 years are 0.53, 0.35, 0.06 mm/day and 0.46, 0.36, 0.05 mm/day, respectively. The primary, secondary and residual compression ratios of MSWs in the landfill cell are 0.0037, 0.0719 and 0.0033. The primary and secondary compression ratios based on field monitoring are higher than that obtained from bioreactor experiments. This indicates that the results from bioreactors may not be suitable to be directly used in settlement prediction.

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